Canadian Electricity Association / Fisheries and Oceans Canada Science Workshop Proceedings: Setting Research Priorities on Hydroelectricity and Fish or Fish Habitat St. John's Newfoundland June, 2004

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ABSTRACT

A workshop was held on June 9-10, 2004 in St. John's Newfoundland under the auspices of the Memorandum of Understanding between the Canadian Electricity Association and Fisheries and Oceans Canada. The goal of the workshop was to further the development of science to guide regulatory decision making related to the hydroelectric industry. Prior to the workshop, three main areas of inquiry were identified; fish passage, flow modification and reservoir management. Scientists from the CEA and DFO discussed the knowledge gaps in the three areas, guided by a series of discussion papers that were prepared and presented by teams of CEA and DFO scientists. The participants discussed the papers, and then developed an agreed list of highest priority areas for research to address the identified knowledge gaps. This report contains the discussion papers, as well as a summary of the discussions, and the key outcomes of the workshop.

RÉSUMÉ

Un atelier a eu lieu à St. John's (Terre-Neuve) les 9 et 10 juin 2004 relativement à un protocole d'entente entre l'Association canadienne de l'électricité et Pêches et Océans Canada. L'atelier visait à stimuler le développement des sciences afin d'éclairer la prise de décisions réglementaires en ce qui a trait à l'industrie de l'hydroélectricité. L'information recherchée portait sur trois principaux domaines cernés préalablement : les passes migratoires, les modifications du débit d'eau et la gestion des réservoirs. Les chercheurs de l'ACE et du MPO se sont entretenus des lacunes à combler dans la connaissance de ces trois domaines au moyen de documents de discussion rédigés et présentés par des équipes de chercheurs des deux organisations. Les participants ont discuté des documents, puis ont convenu d'une liste des domaines de recherche prioritaires afin de combler les lacunes mises en évidence. Le rapport contient les documents de discussion, le résumé des discussions ainsi que les résultats clés de l'atelier.

INTRODUCTION

On 9-10 June, 2004, 39 representatives from Fisheries and Oceans Canada (DFO), the Canadian Electricity Association (CEA), DFO regional offices and electricity companies from across the country, held a workshop in St. John's, Newfoundland entitled "Setting Research Priorities on Hydroelectricity and Fish or Fish Habitat: the MOU Research Agenda." This meeting was the first joint Research Workshop, organized pursuant to Theme 5: "Research and Monitoring" of the CEA-DFO Memorandum of Understanding, signed July 4, 2002. The objectives were to:

- Obtain and discuss current research in the areas of Fish Passage, Flow Modification, Reservoir Science to assist with the interpretation bulletin development currently in process by CEA & DFO;
- Agree on Research Priorities for Fish Passage, Flow Modification, Reservoir Science, Monitoring, and Marine Environment areas;
- Undertake initial discussions on Risk Assessment and the use of the Precautionary Principle by government and industry and;
- Identify next steps to focus joint CEA & DFO efforts to move forward on critical research for hydroelectricity and fish or fish habitat.

The workshop began with a series of presentations, each outlining the contents of a discussion paper written by a team of DFO and CEA science personnel. The discussion papers addressed the areas of:

- Fish Passage;
- Flow Modification and;
- Reservoir Management.

The main presentations were followed by a series of invited presentations discussing issues related to the process of prioritizing research needs. These talks focused on:

- the role of monitoring in the evolving decision making process;
- possible approaches to risk management and decision making under conditions of uncertainty; and
- criteria for assessing priorities.

After each presentation, group discussions were held to elicit comments and suggestions from the audience.

Following the presentation session, the attendees divided into four breakout groups and discussed the knowledge gaps and research needs in the main areas of interest:

- Fish Passage and Flow Management; and
- Reservoir Management.

The sub-groups re-convened in plenary, and presented the outcomes of their discussions, which are contained in Appendix B of this report.

In plenary, the outcomes of the breakout groups were further discussed and summarized, which lead to the creation of an agreed list of priority research areas. This set of priorities is presented in the Key Outcomes section of this report.

As a means of moving forward, working groups were then created, tasked with defining specific research questions and defining the scope of research that would address these research needs. The working groups were directed to report at the next CEA - DFO National Workshop, scheduled for November, 2004. The members of these working groups are listed in the Next Steps section of this report.

KEY OUTCOMES

PRIORITY RESEARCH AREAS

Based on identified knowledge gaps presented at the Research Workshop, participants agreed on the following research priorities.

Fish Passage

1. Attraction & Guidance
    - Factors affecting upstream and downstream fish passage
        - including: design for multispecies & different life stages
2. Hydraulic Conditions
    - behavioural responses to hydraulic conditions
    - facility location & transport in rivers
    - modelling of nature-like (physiomimetic) fishways
    - hydraulics of new fish passage methods
    - hydraulic conditions in fishways and at screens
    - intake velocity & design to maximize fish guidance, minimize injuries and prevent fish from entering turbines
    - hydraulic anomalies
3. Hydrologic conditions relevant to fish movements

Flow Modification

1. Comprehensive Framework for Flow Management
    - ecosystem considerations
2. Natural Flow Paradigm
    - winter flow impacts
    - extreme event impacts
    - production in pristine vs. manipulated rivers
    - ecosystem considerations
3. Flow – Habitat – Population interrelationships
    - Performance measure to determine success – validation

Reservoir Science

1. Habitat
   - structure and type of habitat created and/or lost,
   - role of submerged trees/branches,
   - fish interaction,
   - creation/improvement
2. Mitigative Measures
   - What measures can reduce the impacts of habitat changes, erosion, mercury liberation and vegetation clearing
3. Reservoir Operation Effects
   - Impacts of drawdowns and shoreline erosion on fish and habitat

NEXT STEPS

Several participants agreed to continue discussions on the following areas. The teams listed below are asked to meet (by conference call/email) over the next 4 months and define priority research questions as well as the scope of work. Team leaders should coordinate the discussions and report back at the November 2004 CEA-DFO National Workshop.

Fish Passage

- Attraction, Avoidance, and Guidance.

Team to continue discussions:

Chris Katopodis, DFO C & A (Team Leader)
Keith Clarke, DFO Nfld.
Marie Gaulin, DFO Québec
Ken Meade, NS Power

Flow Assessment Framework

- Review of global experiences needed and how they could be applied.
- Seen as a broader policy issue.
- Must account for fisheries management.

Team to continue discussions:

Michel Bérubé, Hydro-Québec (Team Leader)
Ed DeBruyn, DFO C & A
Marie Gaulin, DFO Québec

Ken Meade, NS Power
Dave Scruton, DFO Nfld.
Hugh Smith, BC Hydro
Terry Toner, NS Power

Natural Flow Paradigm

- What elements of peak flow in hydrograph need to be protected?
- How transferable is the theory to the Canadian Shield?
- Is regional validation of the model required?

Team to continue discussions:

Dave Scruton, DFO Nfld. (Team Leader)
Marie Gaulin, DFO Québec
Paul Higgins, BC Hydro
Chris Katopodis, DFO C & A
Greg Pope, OPG

Reservoir science

- Need to define Scope of Work.

Team to continue discussions:

Karen Smokorowski, DFO C & A (Team Leader)
Bill Brown, Manitoba Hydro
Jean-Guy Jacques, DFO Québec
Larry LeDrew, Nfld. & Lab. Hydro
Richard Verdon, Hydro Québec

ACKNOWLEDGEMENTS

Industry and government leads, Richard Verdon of Hydro-Québec (CEA) and Hugh Bain of DFO Science (DFO), acted as co-chairs for the workshop. Michele Roberge, DFO Newfoundland and Labrador Region, and Brent Sellars, Newfoundland and Labrador Hydro were the local organizers for the meetings. Special mention should also be made of Julie Perrault, formerly of DFO Science, who initiated the process of identifying gaps in hydroelectricity and fish research that lead to the workshop, and of the authors of the papers presented at the workshop, whose diligent and meticulous work focused the issues under discussion. The participants of the workshop all contributed to its success through their hard work, open minded approach and scientific expertise. The success of the workshop was also due in large part to the expert facilitation provided by Lynn Morrissey.

APPENDIX A: DISCUSSION PAPERS

Science gaps for fish passage at hydroelectric projects

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ABSTRACT

Fish passage, including facilities for upstream and downstream moving species, is a subject of increased importance to the hydroelectric industry, particularly members of the Canadian Electricity Association (CEA) and government regulators, principally Fisheries and Oceans Canada (DFO). Biological and engineering research and development have contributed significantly to several aspects of attracting, guiding and transporting fish around dams and power stations. Scientific and engineering studies in both the laboratory and field, along with technological advancements, particularly in tracking fish, have generated and tested several fish passage concepts. Such concepts include fish collection and transport systems, several types of fishways, fish screens, louvers, and fish bypasses. Such facilities may be fairly simple to fairly sophisticated, long-life rigid structures to nature-like adjustable ones, and may be applicable for several fish species and a variety of site-specific conditions. Although some effective solutions may be available for assisting several fish species to navigate through a variety of fish passageways, attracting various upstream migrants or guiding downstream migrants to locate such facilities remain research and development challenges. Fish passage methods for upstream and downstream movements are described, their applicability and state of development for hydroelectric dams is examined, relevant hydraulic, physiological, behavioural and biological knowledge outlined, and science gaps identified. Fish attraction and guidance, relevant fish migration, hydrologic, fish behaviour, hydraulic and biological research challenges are presented. Collaborative DFO-CEA studies may be a productive way to address high priority issues.

INTRODUCTION

Issues involving aquatic life, particularly fish, fish migrations and fish habitat are playing a key role in decisions affecting existing or new works in rivers, including hydroelectric plants, water supply, river restoration and dam removal. Healthy fish populations depend on habitat connectivity, on suitable habitat features which differ between species and life stages, and on river flow regimes which provide sediment, groundwater and nutrient circulation that sustain ecological integrity. Habitat connectivity and fish passage for both upstream and downstream movements are key environmental challenges for water resource projects, particularly existing and new hydroelectric stations.

Fish movements fulfill basic ecological needs that sustain populations, namely: a) recruitment, including the gonad maturation, spawning and nursery phases, b) growth, including juvenile dispersal for optimal use of feeding habitats and c) survival, including predator avoidance and usage of refuge habitats during limiting high or low flows, when harmful environmental conditions occur, or for over-wintering, particularly in ice-covered rivers. Fish migrations are directed movements between two or more habitats, occur with regular periodicity and involve a large fraction of the population (Northcote, 1978). Reproductive, trophic, and survival migrations are ecological imperatives for most fish species. Barriers to such upstream or downstream migrations lead to population decline, reduced biodiversity, and extinction or species replacement (Lucas and Baras 2001). Entire populations of riverine species can be eliminated if either up- or downstream migrations are blocked and if habitats are fragmented or isolated. Different species move and migrate at several key life-stages and under different environmental conditions to fulfill biological needs.

Providing passage for fish assemblages at a barrier is a difficult biological and engineering task and protection of endangered or species of special concern adds complexity. Fish have complex life history strategies that are generally poorly known, yet efficient upstream and downstream fish passage is needed if barrier impacts on fish movements are to be mitigated. Appropriate flows and effective ways to guide fish to ascent and descent of barriers are major issues, particularly for hydroelectric projects. Although research and development related to fish passage has contributed to a better understanding of biological requirements for various species and improved ways to accommodate their upstream and downstream movements, many science gaps remain. Knowledge and research needs are outlined which aim to provide: a) a better understanding of the physical and biological parameters involved in upstream and downstream fish movements in natural and regulated river systems, b) effective ways to attract and guide different fish species and life stages, c) more suitable and safer fish passage systems around hydroelectric stations and d) reduced delays and predation.

Discussion of these topics is divided into the following sections:

- Timing of fish migrations and hydrology
- Fish attraction for upstream moving fish and hydraulic cues
- Fish guidance for downstream moving fish and hydraulic cues
- Fish behaviour and fish passage hydraulics
- Swimming performance and hydrodynamics
- Hydraulics and fish passage for upstream movements
- Hydraulics and fish passage for downstream movements

Timing of fish migrations and hydrology

Fish migrations comprise spatial and temporal movements between spawning, feeding and refuge habitats. Depending on species and life stage, short or long distances may separate these three types of habitat (Lucas and Baras 2001). Fish migrations are classified as oceanodromous, if taking place entirely in the ocean (or at sea), potamodromous, if entirely within freshwater systems (e.g. lake sturgeon *Acipenser fulvescens*, walleye *Sander vitreus*, Arctic grayling *Thymallus arcticus*, kokanee *Oncorhynchus nerka*), and diadromous, if movements between marine and fresh waters are involved. Diadromous fish are usually grouped as a) anadromous, those which run-up rivers to freshwater spawning grounds, but grow mostly in saline waters (e.g. Pacific salmon *Oncorhynchus sp.* and Atlantic salmon *Salmo salar*, American shad *Alosa sapidissima*, blueback herring *Alosa aestivalis*, striped bass *Morone saxatilis*, sea lamprey, Arctic char, alewife *Alosa pseudoharengus*), b) catadromous, those which run-down rivers to spawn at sea, while they grow in freshwaters (e.g. eels *Anguilla spp*), and c) amphidromous, those which run between fresh and saline waters, feeding and growing in both, and with no apparent connection between migration and reproduction (e.g. 'sea run' brook trout, *Salvelinus fontinalis*) (Lucas and Baras 2001; Northcote 1998). Fish migrations are time sensitive, differ between species and geographic regions, and appear to be regulated by thermal, sedimentary and hydrologic characteristics of specific rivers and streams. Water temperature, alone or in combination with river discharge, photoperiod and possibly other environmental stimuli, may be a major factor in regulating fish physiology and reproductive, trophic or survival migrations in many species (Northcote, 1998).

Timing of fish movements is a basic consideration in the design and operation of fish passage facilities (Katopodis 1992b; Therrien and Bourgeois 2000). Although seasonal movements are generally known for many species, specific timing in the river system and at a hydroelectric site is more useful and often lacking, particularly for non-salmonids (Katopodis 2002b; Marmulla 2001).

Biologically meaningful quantitative relationships between biological and hydrological variables are essential for the design and operation of effective fish passage facilities. Examples include: a) the migration timing of different species and life stages and stream or river thermographs, hydrographs, or precipitation, b) tolerable delay and river discharge, or c) habitat suitability and river discharge. Both research and project specific studies in these areas, particularly for non-salmonids, are needed to develop such relationships.

Fish attraction for upstream moving fish and hydraulic cues

A survey of international and Australian fishway professionals in 2000 indicated that fishway entrances are fundamental to the effectiveness of fishways and a research priority (White et. al. 2001). This is hardly surprising, as attracting different species to fishway entrances is probably the most challenging task and may well be the determining factor in fish passage effectiveness, particularly when wide rivers, large regulated flows and a variety of species are involved. Yet empiricism, rather than sound science, characterizes common practices to accomplish this. The complexities of poorly understood responses of different species, particularly non-salmonids, combine with limited ability to quantify detailed hydraulics at scales meaningful for fish to present challenging opportunities for scientific investigations. This emphasizes the importance of adequate biological and hydraulic studies to better understand fish behavioural responses and to provide empirical data on migration paths, staging points, and flow patterns that affect fish movements (Katopodis 2002b).

Scientific research and studies can guide the selection of appropriate locations and suitable design of effective fishway entrances. Auxiliary flows in the form of “enough” extra discharge and “appropriate” water velocities are used to attract fish to fishway entrances in many dams and for many species around the globe (Clay 1995; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001). This practice is based primarily on empirical observations and although the nature of its functionality is poorly understood, it has provided good results, particularly with Atlantic and Pacific salmons, even at large hydroelectric stations. A recent study found that salmon numbers using the Isohaara fishway in northern Finland increased when fishway discharge was increased and the type of fishway entrance was changed from a narrow Denil chute at a high elevation to a wide weir at a lower elevation. Fishway discharge was approximately 1 m^3/s and at times competed with large turbine and spillway flows of about 1000 m^3/s. Tailwater level below the expanded Isohaara hydroelectric station in the River Kemijoki and head drop at the fishway entrance affected successful passage of Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta* m. *trutta*) (Laine et. al. 2002). Location of fishway entrances is a key factor in successful upstream passage and fishways that are located in proximity to competing flows (i.e. power plant tailraces, spillways) are often easier for fish to locate and use (Marmulla 2001). Similarly, knowledge of the migration paths used by fish as they approach a fish passage facility may assist in the location, design, and operation of facilities.

An important aspect of upstream migration in relation to hydroelectric development is to understand the energetic costs (budget) of migration from the ocean to preferred spawning, rearing and over wintering habitats and how passage related to the development impacts this energy budget. Additional energetic costs imposed by the development could include energy expended to find and use fish passage facilities (e.g. fishways), energetics associated with delays in migration (e.g. 'false attraction' to tailraces), or secondary energetics costs (escape from predators, increased exposure to more stressful environmental conditions) (Hinch et al. 1996). This is particularly important for species that do not feed on their upstream migration (e.g. Atlantic salmon) or those that are (e.g. some Pacific salmonids) (Bernatchez and Dodson 1987). These increased energy demands could have immediate effects, such as 'fall back' over the dam, or delayed effects, such as reduced capacity for upstream migration (resulting in spawning in less favourable habitats), late arrival on the spawning grounds, and lower fecundity and poorer quality gonadal products (Hinch and Rand 2000). Fleming and Reynolds (1991), for example, studied the effects of artificial delay on the spawning run of Arctic grayling in an Alaskan stream and found that migratory behaviour was altered by delay, causing spawners to be displaced to areas downstream of their targeted habitat. Control fish reached spawning habitats farther upstream than fish delayed for 3 days or longer. Delayed spawners reached sub-optimal habitat, potentially resulting in lower productivity and possible implications to egg viability and offspring genetics. Thorstad et al. (2003) and Gowan et al. (2003) found upstream migrating Atlantic salmon to be delayed at power plants for up to 71 and 52 days, at a Norwegian and Scottish power plant, respectively. Some species such as anadromous Atlantic salmon return to sea for over wintering, or over-winter in freshwaters, and energy reserves play a large role in survival after spawning.

Studies of upstream migrating adult Atlantic salmon at a power plant at Grand Falls-Windsor, Newfoundland, using EMG telemetry, determined that most fish experienced a degree of migration delay at this facility; however the time spent was less than reported at other facilities (see above). The EMG data suggested the energy expended in relation to tailrace attraction was similar to that expended in immediate downstream reaches and highest energy costs were evident in a difficult natural migratory reach above the plant and in fish passage, especially in relation to fishway entrance (Scruton et al. 2004b).

Although many such studies hint at cause and effect, fish attraction remains a highly complex subject, especially for wide rivers, or when many species and sizes are involved, migrating at different times and under variable environmental conditions, with various and sometimes competing biological and hydraulic criteria (Katopodis 1990; 1999; Lucas and Baras 2001). This is a high priority science gap that needs research. Research on flow patterns (circulation, volumes, velocities, momentum, etc) that lead fish towards fishway entrances and attract them to enter, particularly in the presence of several competing discharges, would be of great benefit. Physical and numerical hydraulic modeling of new or existing hydroelectric dams and field studies at existing generating stations provide opportunities for addressing these research needs.

Fish guidance for downstream moving fish and hydraulic cues

Much of our understanding of fish behaviour has been generated by studies of downstream migrating fish, particularly salmonids, at hydroelectric and irrigation facilities (Coutant and Whitney 2000; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001). Both basic and applied research have, often independently, contributed knowledge about (Katopodis 2002b):

- fish swimming speeds;
- discharge related migration cues;
- sensory mechanisms;
- responses to obstacles and various artificial or natural stimuli;
- behaviour and orientation when moving through various hydrodynamic conditions, such as turbulent flow and accelerating flow.

It is important to understand, measure, and simulate adaptations of different species to: a) buoyancy and hydrodynamic control, b) the ability to detect and avoid physical obstacles that may cause injury, c) attraction to favourable conditions, and d) avoidance reactions based on swimming ability, hearing, vision or other sensory organs like the lateral line. The lateral line is especially helpful to fish in detecting fluid movement, water displacements and pressure waves along their length, as well as supplementing other senses (e.g. vision) in identifying and locating stationary or moving objects. The inner ear helps fish sense the rate of movement change, which is essential in flows with linear or angular acceleration. Although tissue density in freshwater teleosts is 5 – 9 %

higher than water, fats and oils and, in some species, gas-filled swim bladders reduce density to within 1% of water in most fish (Coutant and Whitney 2000). Swimming hydrodynamics assist with buoyancy and body stability, as is the case for fish with swim bladders in which the centre of buoyancy is slightly below the centre of gravity, making equilibrium unstable. This is evident for dead or comatose fish, which float upside down.

The sensory panoply of different species provide them with cues for body orientation, swimming speed, and controlled or passive movement as long as fish are healthy and free of undue stress. These cues are particularly significant in more challenging hydrodynamic environments such as: a) accelerating or decelerating flows (e.g. over natural rapids, structures like dams and weirs, or through turbines), b) turbulent flows, with vortices of various sizes (e.g. below rapids, around rock outcrops or bars, fishway entrances, fishways, fish screens), or c) aerated flows (e.g. rapids, stilling basins, fishways) (Katopodis 2002b). Species may respond differently to water acceleration. For example, significantly more Atlantic salmon smolts passed through a surface bypass with a streamlined entrance (which controlled velocity increase) than over a sharp–crested weir bypass. This contrasts with juvenile American shad, for which there was no difference in the passage rate (Haro et. al. 1998). Evaluation of several surface bypass configurations located adjacent to turbine trashracks at small hydroelectric stations in France (20–85 m^3/s), found that fish diversion efficiencies ranged from 17% to 80% for juvenile Atlantic salmon and sea trout (Larinier and Travade 1999). This wide variation in efficiency was attributed to fish responses to hydraulic conditions at the bypass entrance and in front of the trashracks, as well as bypass location and discharge. Floating louver systems, a widely tested behavioural downstream bypass system, was most effective when the appropriate hydraulic conditions, specifically uniform and constant velocities along the louver with accelerating flows into the bypass, were generated (US Congress 1995, Scruton et al. 2003). Physical means for guiding fish are the most effective, although usually also the most expensive, while the more economical behavioural means are usually least effective (Coutant 2001; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001; US Congress 1995).

The location of bypasses and entrances will depend on the migratory behaviour of the species in question. For example, Atlantic salmon smolts migrate in surface waters, therefore most smolt bypass systems for this species have been constructed with surface entrances (Ruggles et al. 1993; US Congress 1995). In contrast, eels are benthic in nature and a recent comparative study of surface and bottom bypasses at a hydroelectric station in France found the bottom bypass to be more effective for this species (Gosset et al. 2004). Additionally, salmonid smolts tend to migrate as groups, or schools, and as such bypass facilities for these species need to be designed to attract and accommodate many individuals concurrently (Lucas and Baras 2001).

A better understanding of fish movements and behaviour can lead to improvements in the survival rates of downstream migrants at multi-project hydroelectric complexes like the one on the Columbia and Snake Rivers in north-western U.S.A. Major changes to the dams and their operation, made between the late 1970s and early 1990s, improved overall survival of juvenile spring-summer chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) (Williams et. al. 2001). These changes included:

- increased spillway flow releases,
- debris removal from reservoir headwaters,
- more efficient and continuous turbine operation,
- structural changes on spillways to decrease atmospheric gas supersaturation,
- changes to inadequate bypasses and
- facilities to bypass fish away from turbines.

With eight dams in operation and the above modifications, overall system survival estimates for these two species ranged from 31% to 59% (1993-1999), which were comparable to estimates of 32% to 56% when only four dams were in place (1966-1967). Although direct juvenile mortality has been reduced, adult return rates have not improved and remained low, pointing to contributions of other stresses in the salmon populations of the Columbia and Snake Rivers.

The above examples illustrate the importance of species specific, site specific, and structure specific studies to improve fish passage, better understand habitat use, and develop appropriate tools for different projects. Each hydroelectric site has some unique aspects that affect the efficiency of fish passage systems and which must be investigated and carefully considered. Studies and monitoring of existing or new upstream and downstream fish passage systems is an essential component in achieving better results and developing more effective systems. Well-coordinated and comprehensive interdisciplinary studies at several hydroelectric stations, with emphasis on a variety of species and hydraulic conditions, are needed to improve the understanding of fish responses and to meet fish passage challenges.

Fish behaviour and fish passage hydraulics

Fish behavioural responses to biological, physical, and chemical factors are key to improving upstream and downstream fish passage and quantifying river flows and habitat values which avoid effects on fish populations (Katopodis 2002b). In designing, locating, and operating fishways and fish screens, and for estimating instream flow regimes, it is important to develop an improved understanding of daily movements and timing. Factors affecting this include:

- response to morphological and hydrodynamic habitat characteristics,
- photoperiod,
- competitors or predators,
- schooling and
- optical, acoustical, tactile and rheotactic stimuli.

For example, species like American shad (*Alosa sapidissima*) that exhibit schooling behaviour both in upstream and downstream migrations, need more space through narrow openings or bypasses compared to species that may prefer to move single file (Kynard 1993).

Hydraulic and physical characteristics within a fish passage structure may also affect the ascent and descent of various species differently. Haro and Kynard (1997) conducted a videographic assessment during peak upstream migration of American shad and sea lamprey (*Petromyzon marinus*) within a pool-orifice fishway of the Ice Harbor design, adjacent to two resting (turning) pools. They found that American shad used surface weirs exclusively to move upstream and drop downstream, whereas sea lamprey used both surface weirs and submerged orifices. Both species approached weirs from beneath the lower surface of the water jet, or nappe, before sprinting through a short distance of high velocity to pass over them. The lamprey, however, attached and rested at the edge of the weir crest before such attempts. Disruption of migratory movement as well as visual and rheotactic orientation for both species appeared to be inhibited by high water velocities (at nominal fishway discharge approximately 1.5 m/s over the weirs and 2.0 m/s through the orifices), air entrainment and turbulence. American shad occupied low-velocity, low-turbulence pool areas, and both species seemed to spend considerable time and energy repeatedly ascending and descending fishway weirs. Eventually, most lamprey and shad appeared to abandon the fishway route and only a small number reached the fishway exit, even though both species readily entered the fishway (Haro and Kynard 1997).

An understanding of the diel patterns in migrating fish is also critical to the optimization of fish passage structures and operation. Studies of downstream Atlantic salmon smolt at hydroelectric facilities on the Exploits River, Newfoundland, determined that the bulk of passage through the bypass facilities were over a narrow time window, at dusk (Scruton et al. 2004a and c). Consequently, the operation of these facilities could be adjusted over very short time frames to optimize passage success. Conversely, if fish were not passed over this 'window' they resided in proximity to the hydroelectric plant waiting for the next 'window' thereby increasing the potential for turbine entrainment, impingement, etc.

To further adapt or improve the hydraulics of various fish passage systems for effectiveness with different fish species, particularly non-salmonids, studies and testing are required.

Swimming performance and hydrodynamics

Swimming performance and hydrodynamic research provide knowledge and understanding of how fish hold position, move, maneuver and accelerate through their fluid medium, and how they sustain their speeds and endurance. A biomechanical approach to such research in the last century, including laboratory and field studies with various species and methodologies, along with developments in hydrodynamic modelling, provide basic understanding, some quantitative predictions and a foundation for further work (Katopodis 2002b). Fish speed, acceleration, and agility (i.e. high-speed maneuverability) range very widely, both in relation to body size and in absolute terms (Webb 1998). Fish achieve this wide range of abilities using a set of gaits, which are unique combinations of muscle-propulsor-behaviour, each one best suited for a specific narrow range of performance (Webb 1998). Fish outperform analogous steady motion propulsion through vorticity control, gained by oscillating body movements which form and manipulate large-scale vortices as they move along the body and reposition them to advantage through tail motions (Triantafyllou et. al. 2000). Studies of the swimming mode of adult Atlantic and Pacific salmon to overcome high velocity conditions in upstream migration suggest these fish adopt a 'burst and coast' mode of swimming, exploiting small scale velocity refugia, as an energy conserving strategy to overcome these types of obstacles (Colavecchia et al. 1998, Hinch and Rand 1998).

Swimming speeds, endurance, acceleration rates, and agility vary among species, due to body morphology, swimming mode, fish length, and are further regulated by water temperature and other variables (Katopodis 1999; Webb 1998). Fish swimming speeds are classified as burst, prolonged, or sustained. Burst speeds are the highest fish can attain over very short times (endurance <20 s) and engage white muscle fibres. Fish apply burst speeds to capture prey, avoid predators, or negotiate high water velocities. Sustained are low speeds fish can maintain indefinitely without fatigue, and use mostly red muscle fibres. Fish employ sustained speeds for routine activities, foraging, holding, and schooling. The intermediate category of swimming speeds is known as prolonged, with fish endurance from 20 s to 30 minutes ending in fatigue and involves both red and white muscle fibres for locomotion.

There is a large data set from performance tests in fish swimming chambers and respirometers (Katopodis 1999; "Ichthyomechanical Data Base"). In the laboratory fish are placed in closed chambers and tested in one of two ways. For critical speeds, fish are tested repeatedly with increasing water velocity increments over a fixed time interval until fatigued. Critical speed is commonly measured for a specific endurance, usually 30 or 60-min. intervals. For endurance tests fish are timed while facing a fixed water velocity. Laboratory experiments provide data on swimming performance useful for fishway and fish screen design (e.g. Peak et. al. 1997). Field verification is an important aspect as field conditions can rarely be matched in the laboratory, especially for the fish. There is a need to understand swimming ability under non-forced volitional conditions, swimming strategy and performance under turbulent flow conditions (e.g. Enders et al. 2003), and also the leaping ability of migrating fishes, including behavioral aspects, to more fully develop the appropriate biological criteria to assist in the design of fish passage facilities. Laboratory studies with various swim chambers furnish data for non-volitional fish responses. Field studies contribute data for volitional responses over a limited range of conditions and with many variables interacting simultaneously, which are difficult to interpret. Controlled experiments conducted with more realistic test conditions (e.g. Colavecchia et. al. 1998) offer another way to test fish performance and develop better design criteria for fishways and fish screens. There is a need for similar research on the swimming performance of many species, particularly non-salmonids.

Hydraulics and fish passage for upstream movements

Basic hydraulics of several fishway types have been studied, particularly in the last two decades, mostly through physical hydraulic modelling. Overall flow characteristics, discharge rating curves and depth-velocity profiles are summarized for several fishway types by Katopodis (1990; 1992b) based on hydraulic modelling conducted mostly in the 1980's. Further work on basic fishway hydraulics conducted mostly in the 1990's is available for the steeppass (Rajaratnam and Katopodis 1991), Denil (Katopodis et. al. 1997), vertical slot (Rajaratnam et. al. 1992), pool and weir (Ead et. al. 2004), and culvert fishways (Katopodis 1993; Ead et. al. 2002). In general, fishway dimensions and design details affect circulation, flow patterns and velocity distributions considerably, but depth-discharge relationships in a limited way. As comprehensive as the above referenced research may appear, it provides just basic flow properties, such as depth, discharge and characteristic velocities. To date, there is limited study of the complex nature of flow within fishways, velocity distributions, eddy size and strength, or turbulence, all suspected to be important for effective fish passage (Katopodis 2002b).

More recently, comprehensive studies on the hydraulics of nature-mimicking fishways have received renewed interest (Katopodis 2002a; Katopodis et. al. 2001; Komura 1996; Shamloo et. al. 2001; Wang and Katopodis 1999). The senior author pioneered the concept of using natural streams as analogs in an early, successful application of mimicking nature or a physiomimetic approach. During the design and construction of the Liard Highway in northern Canada, in the late 1970's, the stream simulation approach was used for culvert design. Culverts at stream highway crossings were sized to maintain the average stream width and cross-sectional area for the estimated stream discharge corresponding to fish migration periods. Sized for stability at the culvert design discharge, large riprap was placed in the culvert barrels, in patterns resembling passable natural rapids. Culverts were countersunk below streambed and culvert slope was set at the average stream slope for each site. A follow-up biological field assessment at four of these culverts showed that Arctic grayling, longnose sucker (*Catostomus catostomus*) and northern pike (*Esox lucius*) navigated through the culverts and completed their spring migrations without delays. Measured water velocities in the culverts were comparable to those in the corresponding natural streams and at least on one occasion, the presence of sizable rocks, assisted with the establishment of flow under the culvert ice and allowed fish to pass (McKinnon and Hnytka, 1985). Nature-mimicking fishways in the form of rocky-ramps, pool-riffles and other variations are used and evaluated in many countries for a variety of species (e.g. Harris et al. 1998; Katopodis 2002a; Katopodis et. al. 2001). Even though a considerable diversity of species and sizes have used several fishway types (Clay 1995; Katopodis et. al. 1991; Katopodis et. al. 2001; Travade et. al. 1998; Stuart and Mallen-Cooper 1999; Pavlov 1989), fish responses to fishway hydraulic characteristics are poorly understood.

Comments and questions from hydraulic studies of several fishway types provide research topics for controlled experiments with fish and field studies to elucidate this (Katopodis 2002b). It is suspected that fish utilize the low velocity zone near the bottom of plain Denil fishways and avoid the high velocity stream near the water surface, yet direct quantitative evidence of this is lacking. Do fish of differing swimming abilities use different paths to navigate through plain Denil fishways, facing increasing velocities and turbulence as they rise in the water column? Since deeper water and longer spacing between the planar baffles increase velocities, particularly in the low velocity layer, are smaller slower swimmers delayed longer than large fast ones? How do fish respond to the oscillating, highly turbulent and high energy dissipating flows of plain and steeppass Denils? Do the same species respond differently to the different vertical velocity profiles of the steeppass, where low velocities occur near the surface for relatively shallow flows and where maximum velocities occur at mid-depth for deep flows? In a direct comparison of a plain Denil and a steeppass, six times as many migratory Ayu (*plecoglossus altivelis*) moved through the Denil and their mean body length was smaller (Wada et. al. 2000).

The importance of fish swimming behaviour during migration and passage is apparent in studies on the Fraser River, British Columbia, where fish have demonstrated hyperactive swimming patterns, which have been associated with passage failure and mortalities (Rand and Hinch 1998, Hinch and Brattey 2000). During migration, fish adjust swimming pattern when encountering slow, non-turbulent flow to achieve ground speeds to maximize energy efficiency, but they abandon these behaviours when encountering high velocity, turbulent flow (Hinch et al. 2002). Fish often demonstrate a wandering behaviour when they encounter turbulent flow, which is considered a searching behaviour for sustained, directional flow (Kynard 1993). An understanding of these types of behaviours is critical to the siting of fish passage facilities and the provision of suitable conditions for the approach to and entrance of fishways.

It is encouraging that a great variety of anadromous (e.g. Pacific and Atlantic salmons; Clay 1995), catadromous (e.g. juvenile barramundi *Lates calcarifer*; Stuart and Mallen-Cooper 1999) and potamodromous (Katopodis et. al. 2001) species have used vertical slot fishways throughout the globe. More studies are needed though to provide a better understanding of how fish respond to pool turbulence and circulation patterns, including the path and diffusion of the water jet through the slot, all of which are affected by slope, head drop, pool or baffle size and shape (Wu et. al. 1999a). How is fish passage affected in pool and weir fishways where slope, discharge, weir height and spacing affect the flow regime over weirs, as well circulation patterns in the pools? Answers to such questions involve a much better understanding of velocity distributions, circulation patterns and turbulence for various fishways. They further include the ability to predict, quantify and model these hydraulic characteristics at relevant scales, as well as assess fish responses to them.

Initial research in this direction includes hydraulics of fish resting pools (Rajaratnam et. al. 1997) and vertical slot pools (Wu et. al. 1999a), where aspects of circulation patterns, essentially three dimensional complex flow phenomena, are outlined. A study on corrugated culverts provides velocity distributions for round shapes and near the boundary, where fish may take advantage of lower velocities to move through (Ead et. al. 2000). A comprehensive study on weir fishways with various slopes, discharges, weir heights and spacings, covering plunging, streaming, transitional and supercritical jet flow regimes, was also completed. Main flow characteristics are described, velocity profiles are analysed, and a diagram to predict the different flow regimes, was developed (Ead et. al. 2004). Responses of different fish species to the various flow characteristics in pool and weir fishways need further study. Similarly, studies on the hydraulics and field assessment of nature-mimicking fishways need to continue (Katopodis 2002a; Katopodis et. al. 2001; Wang and Katopodis 1999).

Hydraulics and fish passage for downstream movements

Fish may suffer scale loss, injuries, predation or mortality by passing over spillways or being drawn into turbines, irrigation canals, cooling towers, pumping stations, industrial and municipal water intakes. Commonly, several types of fish screens have been used and widely accepted for decades at water intakes, irrigation canals and hydroelectric dams, and their designs are based primarily on empirical applications. Methods to avoid fish entrainment or impingement include physical exclusion, fish collection and removal, guidance systems, behavioural methods, and bypassing fish around barriers (Anderson et. al. 1998; ASCE 1995, 1982; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001; Ruggles and Hutt 1984; US Congress 1995). Physical or positive barrier methods for protecting fish are the most common and widely accepted techniques, offering the highest level of protection for fish and include a variety of fixed or travelling screens. The effectiveness of fish screens is based on the design and hydraulic characteristics of the device, fish swimming capabilities, fish responses and site-specific conditions (Katopodis 1996). Fish screens are considered to offer the highest level of protection for fish and include a variety of fixed (e.g. various shapes of wire mesh, wedge wire, perforated plate, Coanda-effect, etc.) or rotating screens. These are usually fine mesh, corresponding to fish size, and with low water velocities approaching the screens, corresponding to low prolonged or sustained speeds of the species involved. Fish swim in front and along the length of the screen on their way to a bypass exit. The design approach for these screens is to keep water velocities in front of them low enough so fish are in control and have the stamina to escape impingement (Katopodis 2002b & 1992a; US Congress 1995).

The recent attention to downstream fish passage has meant that much of the research and development has been focused on existing hydroelectric facilities, in a retrofit context (e.g. US Congress 1995). In these situations, opportunities to implement downstream passage solutions are constrained by the existing infrastructure of the plant and the current/future operating regime, and it is often only under situations of major plant construction or re-licensing of operations, that downstream fish passage issues can be effectively addressed. Retrofit solutions are frequently constrained in meeting hydraulic and behavioural conditions necessary to achieve high passage success, consequently retrofit passage systems are, in many instances, unique to the facility and often experimental, can be of hybrid design (i.e. include both physical and behavioural components), and frequently are sub-optimal in terms of effectiveness. Considerable ingenuity and innovation are often needed to optimize fish passage solutions at existing power plants

Louvers, trashracks, surface collectors and bypass chutes normally offer a lower fish protection level than fish screens at a reduced cost. Louvers are less expensive guidance devices than screens, but are more dependent on fish size and behaviour. For example, Kynard and Buerkett (1997) tested two experimental louver arrays with an orientation of 20^0 to the direction of the flow, which consisted of vertical slats, spaced 76 mm and 152 mm apart and positioned at 90^0 to the flow direction. Adult American shad were prevented from passing through the slats and responded to the louver arrays as a physical barrier during the day and as a behavioural barrier at night. However, fish avoided entering either a wide-shallow (1220 mm wide by 910 mm deep) or a narrow-deep (460 mm wide by 1830 mm deep) sharp-crested weir bypass exit. This avoidance response seems to be related to the rate of water velocity increase within a distance of 1 m upstream of each exit (Kynard and Buerkett 1997). Behavioural devices (Coutant 2001; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001; US Congress 1995), based on acoustic, electrical, optical or olfactory responses, tend to be species specific; however fish usually habituate to them, thereby contributing to limited success. They usually do not provide an acceptable level of fish protection on their own, but may improve efficiencies if combined with fish screens or louvers. Bypass systems include barging, trapping and trucking, fish pumping, flow spilling at critical migration times, and may be suitable in some cases. Most fish protection techniques have been tested with juvenile salmonids, and testing to meet the needs of other species is needed.

More recently, fish screens operating under high water velocities have been developed or are undergoing testing, as a more economical alternative to low velocity screens (ASCE 1995; ASCE 1982; Cook et. al. 1993; Katopodis 2002b; Lucas and Baras 2001; Marmulla 2001; Ruggles and Hutt 1984; Therrien and Bourgeois 2000; US Congress 1995). The design approach for these screens is predicated on the premise that fish are transported by the high velocities into a bypass without harm. Inclined high velocity screens form a flat surface sloping towards the floor of a pressurized water-conveying channel, leading to a fish bypass at the upper end. Inclined screens include the Eicher screen (Adam et al. 1990), which is fitted in a penstock and an adaptation of this concept, the Modular Inclined Screen, MIS, intended for rectangular open channels (Cook et al. 1993). Inclined high velocity screens have received extensive testing with downstream migrating salmonids and offer high efficiency in bypassing fish, although concerns with descaling and injuries from contact with the screens remain. Angled high velocity screens, consist of vertical screens at an angle to the direction of the flow in open channels. Initial laboratory biological and hydraulic studies on angled high velocity screens show promise and prototype testing is warranted (Katopodis et. al. 2005). Fish screen hydraulics, modeling of flows around screening systems, and testing fish responses and effectiveness need significant and comprehensive research efforts.

RESEARCH AND DEVELOPMENT PROGRAM

Continued comprehensive research and development in several biological and physical study areas, as well as interdisciplinary investigations are needed to advance and apply scientific knowledge to meet the challenges presented by fish passage at hydroelectric projects. There are numerous opportunities both in the laboratory and in the field for contributions to fish behaviour and hydraulics, fish physiology and hydrodynamics, fish movements and hydrology, physical, numerical and biological modeling. Integration of such engineering and scientific studies in a research and development cycle would provide better understanding and additional utility to the results and the effectiveness of their application. Biological and physical laboratory and field studies can form a cycle of research and development, which allows for adjustments as knowledge is gained. Laboratory studies provide an understanding of fundamental processes or quantify key parameters. Field studies force pragmatic application of the concepts, confirm laboratory measurements, and assess fishway or fish screen effectiveness for fish species and life stages under real hydrologic and hydraulic conditions. Mathematical modelling allows hypothesis testing, simulation and prediction. Linkages between specific studies provide for the flow of information and assist with the integration of interdisciplinary knowledge (Katopodis 2002b).

A comprehensive research program benefits greatly from expertise, innovative study methodologies and breakthroughs in instrumentation. Fish passage and fish habitat related studies offer some unique challenges, particularly for controlled experiments with fish. For example, physical models have made significant contributions to the development of hydraulics into a mature science, are well established, and produce reliable results. Taking into account fish requirements, physical modeling can be used appropriately to conduct controlled experiments in near-prototype conditions. Larger flumes, such as the mobile Ichthyo-Hydraulics Flume at the University of Alberta, have already produced tangible results (Anderson et. al. 1998; Colavecchia et. al. 1998; Katopodis et. al. 2005). Various fish passage devices and guidance systems can be tested in controlled experiments with different species.

Technological advances in observing, tracking, measuring, and analysing fish movements, responses, and behaviour, as well as observing, measuring, quantifying and modelling the relevant hydrodynamic phenomena are particularly helpful in the pursuit of better understanding and knowledge both in the field and in the laboratory. More sophisticated uses of older velocimetry techniques (e.g. Wu et. al. 1999b), as well as newer ones such as ADV (acoustic Doppler velocimetry) and PIV (particle image velocimetry; digital and laser) are assisting with measurements and quantification of 2- and 3-dimensional flows. Digital photography and videography assist with image processing that offer a better understanding of flow phenomena, fish behaviour and data interpretation. This technology has evolved to a point where electronic data is becoming the norm and opens numerous possibilities for lower cost fishway monitoring. Research and development of image processing software to obtain automated counts would provide data collection for fishway monitoring and efficiency studies, migration timing and duration, and fish stock assessments. Telemetry and radio tracking using acoustic, code wired and PIT (passive integrated transponder) tags on fish provide data, which was difficult or impossible to obtain in the past. Recent and future developments of physiological telemetry devices such as EMG (electromyogram transmitters measuring swimming expenditure) and cardiac output (transmitters measuring cardiac function) tags will greatly increase our ability to measure the physiological response of fish *in situ* and in real time (Lucas and Baras 2001). Computers and data loggers make the collection and analyses of enormous data sets routine and the development and use of data and computation intensive 2- and 3-dimensional numerical models fairly common (Katopodis 2002b).

Although, as outlined above, the research and development needs for fish passage at hydroelectric projects are large, several more specific and high priority areas are identified. With emphasis on non-salmonids, these include fish attraction for upstream fish passage, fish guidance for downstream fish passage, fish behavioural responses to hydraulic conditions associated with facility location and transport, fish movements in relation to hydrological variables, and hydraulics of novel fish passage methods. Collaborative studies between DFO and CEA and between DFO Regions and CEA member utilities may be a productive way to address such high priority areas of research and development.

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SUMMARY OF GROUP DISCUSSION FOLLOWING PRESENTATION

Chris Katopodis gave a presentation, outlining the contents of this paper. Following the presentation, the participants were encouraged to identify and discuss issues of relevance for Fish Passage, particularly as they related to future research needs. A number of points and suggestions were identified.

- Conduct a single case history study that includes upstream and downstream data; all case histories should be reviewed because of the differences between the effectiveness of techniques for managing upstream and downstream passage of fish.
- Determine key non-salmonid species and reflect regional differences.
- Consider computer modeling; would require good measurements to simulate accurately. Commence on a small scale.
- Design for multi-species and capture life cycle sensitivities.

- Identify the requirements for fish passage and whether any documentation exists. Should link to factors that influence passage and efficiency/cost effectiveness.
- Limited research available on preventing accidental downstream passage.
- Would be helpful to have a Directory that identifies who's doing what, who has expertise, where relevant information is available, etc. Agreed that a "Who's Who" Directory will be prepared.
- The complexity and expense of cleaning and maintaining mesh screens/racks an issue in case studies.
- Potential to damage fish exists with bypass systems studies.
- Studies on the general issue of effectiveness and efficiency are missing.
- Management needs to identify and agree on the overall goals of fish passage; goals may vary by region.
- Build knowledge base in monitoring.
- Study the implications of fish energetics and fish passage.
- Study the hydraulic anomalies being exploited by fish.
- Questions remain with regard to behavioural responses, attraction and guidance and swimming performance.
- Cost effectiveness remains a serious issue.

This input was quite helpful for the prioritization of future research in Fish Passage.

Flow Modification Assessment Methods Related to Fish, Fish Habitat, and Hydroelectric Development: A Review of the State of the Science, Knowledge Gaps, and Research Priorities for Fisheries and Oceans Canada (DFO) and the Canadian Electricity Association (CEA)

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ABSTRACT

This paper has been developed to review the 'state of the art' in flow modification assessment methods; identify knowledge gaps in relation to fish and fish habitat responses to flow modification and in relation to flow setting tools and methodologies; and to identify research priorities for Fisheries and Oceans Canada and Canadian hydroelectric utilities to improve our understanding of the modification issues in a Canadian context. The state of the art in flow assessment is reviewed in relation to four major categories of methodologies, specifically (i) hydrological methods, (ii) hydraulic rating methods, (iii) habitat simulation methods, and holistic methods. A number of new and emerging methodologies and tools are also discussed. Practices currently in use in Canada to assess and establish modified flow regimes in relation to hydroelectric development, largely delineated on a provincial or regional basis, are described. Knowledge gaps and research priorities are identified. The need for a comprehensive assessment framework in Canada that incorporates many scales and approaches to flow modification was identified. Assessment methods must be applicable across a scale of possible hydroelectric development (e.g. mini-hydro through mega projects), types of hydrological alteration and operation (e.g. 'run of river', hydro peaking, flow diversions, load following, multi-year regulation), and the diversity of river types across Canada (e.g. low gradient prairie rivers though smaller high gradient coastal rivers). Integration of the concept of a 'natural flow paradigm', i.e. the need for a variable flow regime, demonstrating the ecological benefits of this concept into modified flow regimens, and determining the essential elements of this variability, is viewed as important. The need for post project monitoring, validation of model predictions and assessment outcomes, and the linkage of monitoring and validation to refinement of the modified flow regimen in an adaptive management context is viewed as an important element of flow regulation. There is a continued need for further development of tools and models to assist in setting flow regimes. Biological modeling, integration of all aspects of riverine ecology, improvement of the resolution of hydraulic simulation methods and predictive ability under winter (i.e. ice) conditions, and development of approaches for use in large river environments are viewed as areas as key areas requiring research and development in Canada.

INTRODUCTION

There are ever-increasing and diverse demands for utilization of river resources globally (e.g. irrigation, hydroelectric development, municipal water supplies, industrial uses, etc.). It has been estimated that over 605 of the world's rivers have been subject to some form of hydrological alteration and in the Unites States over 85% of all inland surface waters are artificially controlled (WCD 2000). Canada has been estimated to have close to 1600 dams, seventh by country in terms of number of impoundments, containing 1.7% of the world's dams (Tharme 2003). Water development projects strive to utilize a portion or all of the available water in a given river resulting in reduction, regulation, and in some instance augmentation (diversion, peaking power production) of flows. These modifications can have considerable serious impacts for riverine biota. Consequently there has been considerable emphasis on the development of tools and methodologies to address the conservation and protection of instream flows while allowing acceptable uses of water. The need to balance the demands of water resource development with the ecological integrity of the aquatic environment is requiring government and industry to develop innovative and effective approaches to water resource allocation (King and Louw 1998). This has led to the evolution of the concept of 'instream or ecological flow requirements' and the development of a science focused on instream flow assessment methodologies.

The electrical sector in Canada is expected to continue to grow and expand to meet continued growth in expected load, to replace costly and environmentally threatening thermal and nuclear power generation, to address commitments to the Kyoto Protocol, and to exploit opportunities for export and sale of hydroelectricity to the USA. The utility sector is also undergoing increasing deregulation and it is expected there will be many new developers in the market and many of new projects will be smaller is size and scope as compared to the mega-projects developed in the last half of the 20th century. New developers will be profit 'focused' and will not have the history and legacy with respect to environmental protection that the large, provincially based utilities have developed. An increasing trend towards a deregulated electric market will lead to a speculative and variable pricing structure for electricity, encouraging operators to produce power when the market demand and prices are highest. Operations will be based on economics and environmental considerations (as a component of project economics). This potentially may result in an increasing trend towards variable hydroelectric operation, specifically hydro peaking, although many existing and future hydroelectric operations are well suited to meet peak demands. Another trend in the utility sector globally is towards a pricing structure that provides a premium for 'green' power; that is power produced by environmentally acceptable means (e.g. solar, wind, hydro), and the prescription of an ecologically acceptable flow regimen will be an important consideration in this certification.

DFO and the Utilities continue to be challenged to mitigate potentially harmful downstream impacts of diversion and/or regulation associated with hydroelectric development. The DFO, with a legislated mandate for the protection of fish and fish habitat, is challenged to ensure that hydroelectric development proceeds in a manner consistent with this mandate. In order to meet the 'no-net-loss' guiding principle of the Policy for the Management of Fish Habitat, reliable and scientifically based methods must be developed that provide conservation of habitat productive capacity. Prescription of a flow release regimen to protect fish habitat and populations, and associated prescribed environmental mitigation must be effective, fair, and scientifically based. While the DFO embraces the 'precautionary principle' to address uncertainty in resource based decisions it must also consider alternative approaches (e.g. adaptive management; multiple methodological applications for flow setting; M. Berube, Hydro Quebec, DFO/CEA Workshop, April 2003) in the application of such a concept. It is contingent on both the DFO and the Utilities to take the lead in developing frameworks and approaches to flow modification, and to integrate the variety of methods currently in use across Canada to provide both flexibility and consistency in application of flow setting techniques.

Owing to the level of uncertainty associated with most instream flow assessment techniques, there is no method or suite of methodologies that could be considered fully scientifically defensible and applicable in all situations (Castlelberry et al. 1996). Consequently, a myriad of methodologies has evolved that reflects various levels of sophistication, elements of jurisdictional and legislative influences, regional differences in evaluation of ecological resources, and societal and ethical factors. It is now widely accepted that a single minimum or optimum stream flow is a myth and there is a need for a dynamic flow pattern to provide the hydrological influence to maintain channel dynamics and to meet seasonal biological requirements. Historically, instream flow assessment methods have been primarily focused on flows required for aquatic species, primarily fish, but recently have evolved to include consideration of values including recreation and other societal needs as well as other components of the entire ecosystem.

REVIEW OF THE 'STATE OF THE ART':

Flow prescriptions may also be made at several levels of resolution from a single annual flow value to more complex modified flow regimes, where the overall 'envelope' of water allocated for environmental purposes is a combination of different daily, monthly, and/or event based (e.g. flushing flows) allocations. The scale at which flow modification assessments are undertaken can vary as well from the watershed level, or multiple watersheds in the case of diversions and inter-basin transfers, to an analysis for a very well defined, specific reach of river. Other major considerations in the adoption of a specific approach to assessing flow modification include the appropriate approach to flow assessment, the processes used in the analyses, time frames for assessment, technical capability and available resources (human, financial, institutional), available data, level of resource protection that is necessary, defensibility of the outcomes, and the jurisdictional context in which the prescription will be conducted (e.g. Dunbar et al. 1998). Accordingly a wide variety of methodologies have been developed to address the broad spatial and temporal scales at which flow assessments are needed and for which various levels of resolution and sophistication have been important.

There have been many reviews on the state of the art in instream flow assessment methods, some from a global perspective (e.g. Annear et. al. 2002; Tharme 1996, 2003), and others from the perspective of application to a discrete geographical and/or political jurisdiction, usually a country or state/province (e.g. Dunbar et al. 1998, IEC-Beak 1985). In these reviews there have been many approaches to categorization of methods and there is some debate in the literature with respect to most appropriate means of categorizing the available methodologies. Methodologies in use and under development range from very simple, reconnaissance level approaches used for broad based water resource planning and feasibility level studies to intensive, sophisticated methodologies for assessment of highly valued watercourses or reaches with considerable public attention (Annear et. al. 2002; Tharme 2003). Petts (1996) identified four main approaches to setting river flow objectives: (i) hydrological indices ('look up' table); (ii) desktop analyses of historical data; (iii) collection of primary field data supported by descriptive analysis; and (iv) detailed flow-habitat-biological response simulation. Caissie and El-Jabi (2003) have classified the methodologies into 3 categories: (i) historical streamflow methods; (ii) river hydraulics methods; and (iii) habitat preference methods. Others have grouped the assessment approaches to flow modification into four relatively distinct approaches or categories including: (i) hydrological methods; (ii) hydraulic rating methods; (iii) habitat simulation methods; and (iv) holistic methodologies (e.g. Jowett 1997, Dunbar et al. 1998, Tharme 2003). The latter categorization has been used to structure this review.

Hydrological Methods

Hydrological methodologies have been variably described as 'desk top' assessments, 'look-up table' approach, 'rule of thumb', threshold, or standard setting approaches. These approaches typically utilize available (historical) or extrapolated hydrological data, usually containing natural flow patterns described as annual, monthly, or daily flow volumes. These methods typically prescribe a fixed proportion of available flow, on an annual, seasonal, or monthly basis, to maintain the appropriate ecological feature or some other measure of river 'health', and these have most often been defined in terms of 'minimum flow' although other thresholds ('desirable', 'optimum') have been considered. These methods are considered to utilize minimum hydrological indices and most often result in requiring a fixed percentage of the mean annual flow (e.g. Tennant's Montana method, Tennant 1976) or an exceedence percentile of a natural flow duration curve (e.g. Jowett 1997). In some instances these hydrological based methods have been expanded to incorporate catchment variables including biological, hydraulic, and/or geomorphological considerations, particularly in regional approaches to standard 'benchmarking'. Further, there have been suggestions for the need to introduce an element of scale into application of standard setting techniques as small streams may require a higher degree of protection than larger systems (Jowett 1997). Some applications have involved efforts to account for inter-annual variability, having alternate indices for wet, dry and normal years (Dunbar et al. 1998). There has been considerable debate about the appropriateness of using a mean value for setting an index as mean values will be considerably influenced by extreme flow events, particularly high flows (Dunbar et al. 1998).

The most widely known and applied hydrological method is Tennant's Montana Method (Tennant 1976) which was developed, based on professional judgment, from 58 streams in Montana, Nevada, and Wyoming. This method is the second most widely used methodology in North America and has been widely applied in other countries (Tharme 1996). Tennant observed that width, depth and velocity, considered important to the well being of aquatic life, were provided to varying degrees of quality in relation to specific percentages of the mean annual flow. He developed a table relating 'habitat health' to MAF resulting in recommendations for percentages of MAF to meet varying levels of habitat protection for fish, wildlife and recreation and the table became the framework of the methodology (Table 1). Supplemental information, such as photographs, can be used to support recommendations. There have been many regional variants of the Tennant method and the Tesseman method (Tesseman unpublished report as cited in Dunbar et al. 1998) is a two tier modification of Tennant's approach, incorporating monthly minimum flow limits.

There are many other variants of hydrological methods including: the Median Monthly Flow (MMF)(ref), the Q_{50} (USFWS 1981); the New England Aquatic Base Flow Method (ABF) (Kulic 1990), the 7Q2 Method (Belzile et al. 1997), the 7Q10 Method (ref.), and others (Reiser et al. 1989). A common approach has been to conduct an analysis of flow duration curves, displaying the relationship between discharge and the percentage of time that it is exceeded. Flows are analyzed over specific time periods, typically monthly or annually, or time periods may be aggregated by biological significance (e.g. fish spawning). The resulting recommendation is typically a flow percentile (e.g. 40th percentile or Q_{40}).

These methods generally are characterized as being rapidly applied, requiring low resource commitments, but they however result in low resolution, often conservative flow prescriptions. These methods are therefore considered best applied as planning level tools, as a reconnaissance level approach or as part of a screening process, or possibly used in situations of low sensitivity and public concern, or alternatively they could be developed as 'preliminary flow targets' (Dunbar et al. 1998, Tharme 2003). Some advantages of these methods are ease of use, low cost, and the wide acceptance and consistent application of the methods. Conversely, if hydrological data are unavailable they must be extrapolated, the method does not consider flow variability, there are geographical limitations to application, and extrapolation the selection of protection levels is arbitrary, and there is no quantifiable relationship between flow and aquatic health. The major shortcoming of these methods is that all flows above the prescribed (e.g. minimum flow) amount have been considered 'available for use' thereby providing limited opportunity for negotiations between competing uses.

It is now widely accepted that there is a need to provide a dynamic component to the flow pattern for regulated systems. As such, method development has moved away from fixed percentage approaches to assessing the annual flow cycle including specific flow events and considering aspects of duration, timing, magnitude and frequency. These methods are currently considered to have utility in a strategic, broad scale approach for setting regional goals for flow conservation or as first level analytical tool in a phased approach for setting flow requirements. These methods have historically, within Canada and elsewhere, been used to set river specific flow objectives however they are currently not considered appropriate for establishing flow requirements for specific projects in most circumstances as they do not incorporate the concept of a natural flow paradigm and often result in overly conservative flow recommendations.

Hydraulic Rating Methods

Methodologies evolved from standard setting approaches towards techniques that implicitly considered a quantifiable relationship between the quantity and quality of instream resources (e.g. fish habitat) and river discharge. These methods were intended to examine the incremental effects of changes in discharge on certain river characteristics, most commonly spawning, rearing, and passage requirements considered important for recreational, economic, or of special status [e.g. endangered]) fish species. The important distinction between an incremental method and 'standard setting" or fixed flow method is that a flow recommendation does not directly arise from an incremental method, rather the process may lead to a flow recommendation after discussion and interpretation of results. From these basic considerations, two groups of transect based methodologies then evolved, based on data requirements and general approach, specifically *hydraulic rating* and *habitat rating* (preference) methods (Stalnaker 1979).

Hydraulic rating methodologies use changes in simple hydraulic features, such as wetted perimeter (width) or maximum/minimum depth, usually determined along single or multiple transects, or transects considered to be limiting or 'critical', as surrogates for habitat attributes known or assumed to be important to biota (e.g. Loar 1986). These methods are based on a quantifiable estimate of some stream resource, fish habitat for instance, and river discharge. The assumption is that there is some threshold value of the hydraulic variable, which when modified, will maintain some level of ecological integrity. Commonly, discharge is plotted against the hydraulic variable of interest and a breakpoint (or inflection point) is selected as a threshold below which habitat quality can become seriously degraded (Gippel and Stewardson 1998). This threshold value is then often defined as a fixed percentage of available flow. These methods utilize simplified prediction techniques to reduce the need for intensive field surveys. These methods have been described as 'mid-range' methods between fixed discharge (standard setting) tools, in that they require some collection of field data, and more intensive habitat hydraulic simulations. Hydraulic rating methods have tended to focus primarily on 'rearing' or 'maintenance' flows for target riverine biota where rearing refers to meeting all life history requirements for fish from hatching to spawning (Stalnaker and Arnette, 1976). In some applications, consideration for additional watershed variables (e.g. basin area, mean altitude, slope, etc.) are included (Tharme 2003).

There have been a variety of hydraulic rating methods developed including the Wetted Perimeter Method (WPM), the Critical Area Method, the One Flow Method, the Colorado Method, and others (Stalnaker and Arnette, 1976; Tharme 2003). The Basque method is considered an innovative hydraulic method based on the 'river continuum concept' relating wetted perimeter to benthic invertebrate species diversity suggesting different levels of protection for polluted and unpolluted river sections (Docompo and de Bikuna 1995).

The most common of these approaches has been termed the Wetted Perimeter Method (WPM), the third most commonly used flow assessment technique in North America (Reiser at al. 1989; maybe this is not as popular a method now though; this applies to other similar comments on other methods), based on the hydraulic relationship been flow and river width (wetted perimeter). The method identifies a minimum flow that will protect the 'habitat needs' on the basis of a wetted width-discharge relationship, with the point of maximum curvature (inflection point) considered the threshold below which there will be rapid reductions in stream width (habitat) with further flow reductions. An important consideration in applying this method is the selection of appropriate points (transects) in the stream to develop the discharge-wetted perimeter relationship. These transects should be both 'representative' (a suitable index of habitat throughout the stream reach affected) and 'critical' (sites where there would be dramatic changes in stream width with flow, for e.g. broad shallow sections, e.g. spawning riffle). The method assumes that if habitat requirements are met in a critical reach (riffle) they will be met in other habitat types (e.g. pools, runs). This method has been most often used in studies to address habitat conditions in critical areas and has also been commonly used for setting fish passage criteria. Several authors (e.g. Gippel and Stewardson 1998) have found the method to be error prone and have proposed improvements to the approach (i.e. mathematical determination of the 'inflection point').

One common feature of these methods is that they implicitly take into account the hydraulic geometry (width X depth X velocity) of the river. When one variable does not change significantly with flow, e.g. width, then there may be a significant change in the other variables, e.g. depth and velocity (Caissie and El-Jabi 2003). It is now widely recognized that depth and velocity are important components of a fishes' microhabitat and that changes in addition to wetted perimeter can affect habitat quality. Ghanem and Hicks (1992) have suggested that a better approach would be to identify the critical stage in the field, rather than the point of maximum curvature on a plot, and use hydraulic analysis to determine flow associated with this stage.

Habitat Simulation Methods

Hydraulic rating tools are considered the precursor to, and/or component of better developed, sophisticated approaches which have been variably termed habitat rating, habitat simulations, microhabitat, or habitat modeling approaches (Dunbar et al. 1998, Tharme 2003). This suite of methodologies involve detailed analyses of the incremental change in quantity and/or suitability of available instream physical habitat for target fish species, life stages, or fish communities (assemblages) in relation to flow modification. The models integrate these hydrological, hydraulic, and biological response variables and through application of hydraulic simulations and biological 'models' of varying types and sophistication (Berube et al. 2002). Hydraulic simulations usually include microhabitat attributes such as depth, velocity, substrate composition, and cover features, although recently more complex hydraulic indices (e.g. Froude number, shear stress) have been included. Variables used in simulations are those directly related to changes in discharge and are not necessarily those that are most important to the well being of the species/life stage. Simulated conditions are then linked with microhabitat conditions considered suitable or unsuitable, usually expressed as habitat suitability or preference functions (usually a normalized index from 0 [unsuitable] to 1 [optimum]) for specific species, life stages and or assemblages or for specific activities or life cycle requirements (e.g. spawning, rearing). An alternative approach is to express preference as 'preferred habitat', 'indifferent habitat' or 'avoided habitat' (Harby et al. 2004). The resulting analyses using these two components usually results in a habitat discharge relationship (e.g. weighted usable area or WUA curves), which are then examined empirically or through other more subjective approaches to prescribe an appropriate flow regimen. Interpretation of the discharge habitat relationships can assist in identification of optimum, minimum, critical, or some other expression of flow requirement for key life history requirements (spawning rearing, migration, over wintering) and, in some instances, for identification of potentially limiting habitat conditions. This incremental relationship between flow and habitat quality/quantity allows for assessment of the 'relative' tradeoffs and benefits between species/life stages and permits negotiation between competing uses. Habitat modeling fundamentally shifts the focus of an instream flow assessment to a specific target species/life stage rather than to river management and/or exploitation.

Habitat simulation modeling has increased in prominence as a preferred tool for allocation of river flows in many jurisdictions and has replaced standard setting and hydraulic rating methods, which rely extensively on professional judgment. Habitat simulation methods can be conducted as stand alone assessments or can be incorporated into broader assessment frameworks which integrate other ecological considerations, provide the opportunity for public involvement and stakeholder participation, provide the context for negotiations and legal resolution, and generally allow for a common approach across a variety of jurisdictions.

The most well known of these frameworks is the Instream Flow Incremental Methodology (IFIM) but a variety of similar assessment frameworks have been adapted from the IFIM and tailored to the needs of a particular jurisdiction. The framework intrinsically recognizes that micro-habitats must be investigated in the context of the larger macro-habitats that influence them. Currently, an IFIM-type approach has been widely applied, and is defensible, when in-depth study of key target species is required and consequently many countries have adopted and/or adapted this approach for their purposes (Dunbar and Akerman 1998). A common element of these frameworks is that they can be applied in an overall consistent and national/regional context, incorporate a hierarchy of approaches that can be applied to a variety of applications, they are flexible in application, and can accommodate developments of new techniques and applications.

Biological criteria used in habitat-hydraulic models are necessarily those parameters that are directly related to streamflow and channel hydraulics and vary both laterally and longitudinally in a river. These typically include depth, velocity, substrate, and (occasionally) cover and are usually measured and modeled on fine spatial scales (micro-habitat criteria). Physical habitat attributes not related to discharge are not normally considered. Parameters that vary longitudinally in the stream (e.g., temperature, DO, macro-habitat variables) are included in some frameworks (e.g. IFIM). Biological criteria are most often developed separately for individual species, specific life stages of a species, and occasionally for species groups (e.g., guilds) with similar habitat requirements. Species and life stages are selected, for the most part, based on (i) management criteria (important for economic or other criteria, e.g., recreational fish), (ii) indicator species (narrow tolerances; if conditions met for indicator species are assumed to be suitable for other species); (iii) rare and endangered species, and (iv) fish that are competition or forage for important species. Biological criteria can be taken from the literature, but there is increasing attention to development of site-specific criteria or evaluation of non site-specific criteria for transferability. A wide variety of approaches are used to develop criteria, the most common being the underwater observation of fish position (and behaviour) and subsequent measurement of the habitat variables associated with that position. Similarly, a wide variety of methods are available to construct criteria curves or some other expression of habitat preference.

Development of biological criteria, and use in habitat-hydraulic models, involves a number of inherent assumptions that are often not met. Commonly, other biotic and abiotic factors important in determining fish habitat preferences are not considered. There are concerns about ecological validity, geographic transferability, seasonal variability, and the multiplicity of inter- and intra-specific interactions which have led to extensive criticism of the methods, and in particular the biological modeling components and approaches. Much of the current focus on improving the science of habitat hydraulic simulation is focused on the shortcomings of current biological modeling approaches.

IFIM/PHABSIM

The most well developed and widely applied habitat preference method used in North America (Reiser et al. 1981), and elsewhere, is the Physical Habitat Simulation (PHABSIM) contained within the Instream Flow Incremental Methodology (IFIM) (Bovee 1982) and these will be discussed in detail to illustrate concepts and approaches common to many habitat-hydraulic simulation frameworks. PHABSIM is a series of computer models linking open channel hydraulics with known elements of fish behaviour and is used within an IFIM framework. The IFIM process is broad in scope and essentially provides an over arching framework for conducting instream flow assessments, integrating planning concepts, analytical models of physical and chemical parameters, alternatives analysis, and negotiation. There are a large number of other components of the IFIM which can, for example, integrate temperature effects and allow a 'network' analysis. The PHABSIM model was originally developed to analyze effect of flow changes on important fish species (e.g. salmonids), but has since been applied to the instream flow needs of invertebrates, wildlife, for determination of flushing flows, riparian vegetation, channel maintenance, water quality, and recreation. Recent versions of the PHABSIM model have greatly increased the capability of the system, for example incorporating higher resolution (2D) hydraulic models, providing flexibility in depicting spatial habitat distribution, and including temporal analyses tools (e.g. a time series component).

PHABSIM uses a number of hydraulic models (e.g. WSP [a step-backwater method], MANSQ [a method employing Manning's equation], IFG4 [uses rating curves and output from the other models]) to describe and quantify the physical habitat. The requirement for field data collection varies with the hydraulic model used and the conceptual approach to modeling. There are a variety of approaches to modeling a river segment with two most common being: (i) selecting and modeling a 'critical' or representative reach involving multiple transect selection within one or more reaches, and (ii) stratified selection where a single transect is placed in several reaches representing available habitat types, and transects are distributed according to the proportional availability of habitat types. Most habitat modeling frameworks use a stream segment (defined as relatively long stretches of stream between confluences with consistent morphology) as the base unit for assessment. These reaches can be defined as critical (i.e. have some potential relationship to limiting fish population levels), representative, or may be stratified based on a meso-habitat approach (Scruton et al. 1998). Bain and Stevenson (1999) provide an overview of methods available for characterization of aquatic habitat, at a variety of scales, including sampling strategies, data collection, limitations and possibilities.

A wide variety of approaches have been used to develop habitat criteria (preference curves, habitat use curves, etc) as biological modeling components. Habitat preferences have been developed and applied at the micro- (e.g. Bovee 1986), meso- (e.g. Parasieciwz 2002), and macro-habitat (e.g. Scruton and Gibson 1993) scale for use in habitat hydraulic modeling. Variables that have been used include velocity (mean, bottom, surface, fish nose, or at other strata), depth, substratum (size, roughness, shear stress), vegetation, and cover (instream, riparian, overhead [shade]). Most common approaches for data collection for development of biological criteria is through underwater observation, mostly through snorkeling and/or diving, and electrofishing (point or area sampling, backpack, boat, and pre-positioned electrofishers) (Bovee 1986). Other methods have been used including radio telemetry (e.g. Scruton et al. 2002), observations from above the water surface (e.g. Heggenes 1990), using underwater viewing boxes and netting or long lining (Harby et al. 2004). Hydroacoustic and video methods have also been applied to larger rivers (Casselman et al. 1990). Sampling strategies can be random or stratified (e.g. transects) and can include a certain degree of spatial and/or temporal replication.

Habitat models are normally developed as habitat suitability or preference functions (curves) and many different methods are used in collecting data and computing habitat preference functions. Initially, biological observations/data are used to develop univariate suitability or preference criteria (curves), most commonly through curves fitted to frequency histograms. These curves can be used to simply reflect habitat usage (utilization curves) but can also be considered to reflect 'preference' if adjusted for habitat availability. These functions are normally computed separately and the resulting curve coordinates are used as input to the model. The model can calculate composite habitat suitability value(s) from the univariate curves using several simple approaches (e.g., straight multiplication, geometric mean, weighted average, lowest limit). Weighting factors and other statistical manipulation of the data can be performed, but these must be conducted outside of the PHABSIM modeling environment. The model output is 'available habitat' which may be computed for each component attribute, however the most common output is an incremental curve depicting the weighted usable habitat area (WUA) in relation to discharge for all variables combined. Weighted Usable Area has been characterized by Bovee (1986) as the 'carrying capacity based on physical habitat conditions alone' and output is intended to predict habitat potential, not fish standing stocks. Depending on the modeling approach adopted, the output can be weighted by the proportional distribution of habitat (types) in the river reach, segment or larger unit (e.g. watershed).

There has been considerable debate as to the appropriate methods for data collection to develop criteria curves and, most recently, with particular reference to the need to consider available habitat in criteria construction. Previously curves were often constructed considering fish habitat use, subsequently adjusted by available habitat, in order to create 'preference functions.' It had been originally considered that adjusting curves based on habitat availability would allow them to be more easily generalized and transferred (e.g. Beecher 1995), however, other biases have become apparent in this approach. Currently, the preference is to develop a sampling methodology that considers available habitat, and not to explicitly adjust curves, such as an 'equal area sampling method' where all habitat types are sampled equally within a defined reach. Another issue is the requirement to construct river-specific habitat criteria and the costs (effort) associated with this activity. The USFWS (NBS) subsequently developed tests for criteria transferability (Thomas and Bovee 1993), however, it was subsequently recognized that field data collection for transferability tests were often not appreciably less than those required to develop river-specific information.

Recently, much attention has been paid, and a wide variety of approaches used, to model multivariate habitat selection and to attempt to consider inter-dependence of variables. These have included exponential polynomial functions and have involved treating all variables equally or using some method of weighting the variables, through an indexing approach based on secondary statistical analyses (e.g. principal component analyses (e.g. Jones et. al. 2003). Logistic regression, a multivariate linear model, has become a common tool to develop habitat probability models as it can accommodate non-normally distributed data and accounts for interactions between variables (e.g. Jones et.

al. 2003; Leclerc et al. 2003; Parasiewicz 2002). In a logistic regression approach, habitat choice is described by the model as 'probability of occurrence' which can be converted to a habitat suitability score (Harby et al. 2004). These multivariate approaches are considered to offer better perspectives on model validation and may have greater potential for transferability to other rivers (Leclerc et al. 2003).

In rivers that are characterized by high biodiversity containing several important fish species a fish community approach has often been applied (e.g. Bain 1995). Again multivariate statistics are used to develop relationships between physical habitat variables and species assemblages (species with common habitat requirements, life history traits, etc.). Some have found that catchment scale variables are useful in describing hydraulic variability and community structure and can further be improved by including instream habitat variables (e.g. Pusey et al 2000). Generally, most modeling tools are single species focused and fail to consider the complex structure and processes in communities in species-rich rivers and community based quantitative models are widely lacking (Harby et al. 2004).

PHABSIM, while widely applied throughout North America, has been the subject of many extensive critical reviews (e.g. Orth and Maughan 1982; Shirvell 1986; Scott and Shirvell, 1987; others) and authors have criticized the biological relevance of the models, the transferability of habitat criteria, the failure to consider biotic/abiotic factors in models, and the lack of validation studies. It has been extensively demonstrated that the choice of habitat criteria and biological model has the greatest influence on the outcome of the modeling exercise and subsequent flow allocation decisions, and the choice of biological criteria input are often arbitrary and subjective.

As the IFIM and similar frameworks continued their development, other model outcomes were defined to address the temporal aspects of flow variability and biological requirements (e.g. habitat time series and various habitat-flow exceedence curves), to potentially explore habitat limiting periods (e.g. Milhous et al 1990). Early applications of this concept applied the WUA/discharge relationships to the daily mean hydrograph, or other time increment, to describe habitat availability over time. The validity of the approach was limited by applying a single WUA/discharge relationship, established at one flow/time, across broad time scales and was further compromised by not considering temporal variability in the habitat requirements of target species. Some practitioners have used 'seasonal' habitat duration curves to attempt to accommodate these temporal aspects (e.g. Gustard and Elliott 1997).

Holistic Approaches

Recently more global approaches to the evaluation of flow modification have emerged described as 'holistic methodologies' (e.g. Tharme 2003; King and Louw 1998). These methods are viewed as using an ecosystem approach to define flow modifications and have been put forward as the new paradigm in environmental flow assessment. Holistic approaches define criteria that describe critical flow events and/or variability for all major components of a riverine system (watershed). A 'top-down' or 'bottom-up' approach is then used to combine the various components under consideration often resulting in a prescribed modified flow regime that encompasses month by month (or more frequent) and element by element features that are well defined and targeted to achieve specific objectives (e.g. ecological, social, etc.) (Tharme 2003; Arthington et al. 1998). These approaches are multi-disciplinary and complex in nature and typically employ many of the hydrological, hydraulic and habitat simulation tools that are components of the various assessment approaches described above. Many countries have incorporated elements of a holistic process into an IFIM-type framework and vice versa.

The DRIFT (Downstream Response to Imposed Flow Transformations) process, which arose from the Building Block Methodology (BBM), is one such holistic method addressing all biophysical aspects of a river. The analysis is conducted by a multi-disciplinary team in a workshop process, and is a scenario based, iterative approach looking at a number of possible future flow regimes (scenarios) (Brown and King 2000). The BBM is a 'bottom up' prescriptive approach that identifies a preferred condition for a river after alteration and then a flow regime is developed to meet this condition (King and Louw 1998). The DRIFT process is 'top down' in that it takes the existing (natural in some instances) flow regime and describes all consequences of flow alteration, detailing the quantitative links between changing river condition in a socio-economic context. The process results in a recommended modified flow regime, a description of the river condition for this regime, the socio-economic impacts including mitigation/compensation, and a quantification of system yield (water required for the ecological flow requirements (EFR) and water available for off-stream use). A common element of these approaches is the consideration of expert opinion in a highly structured setting and the setting of 'interim' flow objectives thereby focusing the effectiveness of further study and analyses along the process of determining the final flow regime recommendation.

Other Methodologies

Many assessments of flow modifications are conducted within habitat modeling frameworks that are based on, or have been developed from, the IFIM and many of these frameworks have been developed within specific geographical and jurisdictional considerations. A listing of many currently utilized modeling frameworks, adapted from Parasiewicz and Dunbar (2001), is provided in Table 1. Some of these frameworks include RHABSIM (Payne 1994), RHYHABSIM (New Zealand, Jowett 1989), EVHA (France, Ginot 1995), and RSS (Norway, Killingveit and Harby 1994). The RCHARC model (Riverine Community Habitat Assessment and Restoration Concept) is a novel framework which looks at cumulative effects of regulation and alteration, with mitigation and restoration, in a scenario testing approach (Nestler et al 1996).

Dunbar et al. (1998) found that many jurisdictions have adopted a two-tier system for flow assessments moving from a basin wide, scoping analysis for 'level one' studies to more detailed, rigorous, scientifically defensible approaches for 'level two' needs. This hierarchy moves from simple standard setting assessments, often focused on a single (minimum) flow, towards a continuous incremental approach involving quantification of the various flow/ecological tradeoffs, enabling various management options to be evaluated. There are also a number of other methodologies that incorporate characteristics of more than one of the major assessment approaches, and have been dubbed 'hybrid' or 'combination' approaches. Tharme (2003) has identified a host of other assessment tools which are not based on the relationship between habitat, biota and flow but have been developed for application to other environments (e.g. lakes and wetlands, estuaries, marine coastal areas, groundwater systems), other aspects of the aquatic regime (e.g. water quality, geomorphology, sediments, riparian areas), and for other biota (e.g. invertebrates, other vertebrate than fish). There are other methods which have adopted a completely different approach, such as multivariate statistical methods (see below) (Dunbar et al. 1998).

It is now widely accepted that there is no single minimum or optimum river flow and that there is a need to develop the knowledge and tools to incorporate seasonal and inter-annual dynamics into regulated flow regimens. Scientific evidence has accumulated supporting a 'natural flow paradigm' where the flow regime of a river, including elements of variability, magnitude, frequency, and duration, and timing and rate of change are considered critical to maintaining the integrity of the ecosystem (e.g. Poff et al. 1997, Richter et al. 1998, Rosenberg et al. 2000). A major focus of recent developments in habitat hydraulic modeling capability has been the development and inclusion of approaches for considering a temporally dynamic pattern in a regulated flow regime. Richter et al. (1998) for example developed a 'Range of Variability Approach (RVA)' to assess hydrological alteration within watersheds. With this increased focus on variable flow regimes through time it has become equally important that there is an equal need to consider and incorporate seasonal aspects of organism's habitat requirements and, for example in several jurisdictions in the Northern hemisphere, a new focus has been placed on the winter season.

NEW AND EMERGING METHODOLOGIES AND TOOLS

Multi-Dimensional Hydraulic Modeling

An area of considerable development over the last decade has been in the improvement of the spatial scale in the hydraulic models, moving from a one-dimensional (transect based), approach to development of 2-D models and recently 3-D modeling, spurred on by increasing computational power of modern computers (Leclerc et al. 1995; Bovee 1995; Olsen and Stotseth 1995). The choice of hydraulic model will depend on the required resolution of results, resources available for filed data collection ands model simulations, and most importantly the resolution of the component biological models (criteria). Regardless of the capability of the hydrodynamic model, the calculated habitat quantity and quality is most sensitive to habitat criteria/models used to transform hydraulic variables into habitat calculations (Waddle et al. 2000).

Recent advancements in simulation tools are utilizing two-dimensional hydraulic modeling to provide a more detailed representation of hydraulic conditions, in turn to provide a finer description of spatial, and in some instances temporal, distribution of habitat. Two-dimensional models offer superior resolution in complex flow situations (e.g. eddies, traverse flow, split flow) and these areas may be critical habitats for aquatic species (Waddle et al. 2000). Conversely, many 2-D hydraulic models in development and use (e.g. HABIOSIM, River2D, RSS) have some difficulty simulating well river edge (riparian) conditions and hydraulics of rivers with high bed roughness at low flows, particularly when roughness elements protrude above the water surface (Smith et. al. 2002). The more spatially accurate predictions provided by 2-D models allow the opportunity for improved habitat simulations and the development and inclusion of new habitat based metrics.

More detailed hydraulic modeling can permit the development and inclusion of more sophisticated biological models that incorporate aspects of inter- and intra-specific competition (e.g. distance to cover; distance to competitors/predators; etc.) (Harby et al. 2003). It has long been recognized that the juxtaposition of habitat patches is important if the overall context of habitat suitability, and this consideration, and others in the science of landscape ecology, are areas where new habitat metrics may be beneficial (Bovee 1996). Several new approaches to biological modeling have been developed from bioenergetic considerations including feeding behaviour and food availability (see below). Some other models incorporate consideration of benthic re-colonization by invertebrates after dewatering of a stream bed. Many of these approaches to biological modeling are only possible if accompanied by multi-dimensional hydraulic modeling.

Three dimensional models (e.g. a component of the RSS, Alfredsen et al. 1997) are also being developed and tested but they require intensive computation which has limited widespread application, testing, and validation. An important aspect of these models is the application of a 'nested grid' which permits use of different spatial resolution within the model, thereby permitting detailed resolution of important ecological areas (Parasiewicz and Dunbar 2001). There is some expectation that 3-D models may be particularly suitable for species/life stages closely associated with the substratum (e.g. Atlantic salmon juveniles) (Scruton et al. 1996).

Models for Invertebrates

The CASIMIR model (Computer Aided Simulation Model for Instream discharge Requirements in regulated streams) contains a suite of models including a hydraulic simulation model based on shear stress which operates at a very high spatial resolution (Jorde 1996). The relationship between hydraulic forces and the substrate is important in determining habitat attributes and this has led several researchers to investigate the use of 'bottom shear stress' as a predictor of habitat quality, particularly for benthic species such as invertebrates.

5M7 Fish Meso-habitat Model and 'Hydrosignatures'

The 5M7 is a fish meso-habitat model recently developed by CEMAGREF (Le Coarer and Dumont 1995), initially employed for fish investigations in the Durance River, southern France. The model calculates preference coefficients (similar to composite HSIs) related to meso-habitat data collected from a fish sampling effort at a variety of scales (micro, meso). The model will also conduct analyses based on population level bio-energetics for taxa in relation to characteristics of the hydro physical environment. It also has been used to evaluate population dynamics in relation to the flow regime and hydrology. Initially the 5M7 model was developed to calculate meso-habitat preference coefficients on the Durance River to describe fish habitat linkages and to evaluate the ecological impact of the observed regulated flows. Bioenergetic species 'trajectories', in 3D representation, were developed using individual fish lengths and depth and velocity values at holding positions linked to local hydraulic variables.

CEMAGREF is also developing the modeling tools based on a digital terrain mapping applied to riverine habitat modeling. This uses the three-dimensional hydraulic model SSIIM (developed by SINTEF and NTNU in Norway) linked to a habitat model based on and field investigations of habitat use, topography and hydraulic parameters. Topographical description of rivers is made with vertical density increasing with terrain complexity (adapted from geodesic techniques). Polygons of homogenous area of substrate, vegetation, etc. can be described by topography. The digital terrain model is based on finite element principals (triangular basis) and cross-sections and longitudinal profiles can also be generated. Results are used as input data to the SSIIM model and the habitat can be modeled at different scales from reach to microhabitat. The entire modeling framework is being developed under the conceptual title of 'Hydrosignatures'.

Bio-energetic Models

Recently new modeling strategies have been developed to describe the effect of changing river conditions on fish and one approach that has received considerable interest has been based on a mathematical model of fish energetics (bioenergetics) (Hughes and Dill 1990; Addley 1993). This is a considered a functional modeling approach based on energy balance assuming fish will strive to maximize energy gain (food intake versus energy related to foraging and holding position). Further development of this approach involved combining a foraging/energetics model with a growth model to describe changes in growth related to flow and temperature alterations. Intrinsic to the use of this approach is the need for multi-dimensional hydraulic simulation, knowledge key behavioural information (intra- and inter-specific competition), feeding patterns, and food availability (Hardy and Addley 2003). While these approaches have received considerable developmental interest, they have been rarely used in a practical application to establish a modified flow regime.

Fish Population Based Models

Population based models are considered a 'process based' approach that integrates the effect of a variety of biological processes across the range in life history attributes and habitats necessary for these life stages, without the necessity of understanding in detail the processes. Several models have taken the approach of linking 'habitat supply' to predict the size and/or structure of fish populations on the basis of habitat quantity and quality in order to assess implications of habitat alterations on fish populations. The most well known of these models is SALMOD, a freshwater fluvial salmonid population dynamics model, developed to enhance the predictive capability and functionality of the Instream Flow Incremental Methodology (IFIM) (Bartholow et al. 1993; Williamson et al. 1993). The model assumes that fish mortality is directly related to the hydraulic and thermal characteristics of micro- and meso-habitats, that vary temporally and spatially, and in relation to stream discharge. The biological model is life history based and tracked by cohorts and habitat supply is computed using PHABSIM yielding estimates of weighted usable area (WUA) of habitat. Nehring and Anderson (1993) used PHABSIM to investigate the effect of flow related habitat changes on rainbow trout and brown trout populations in a Colorado stream using a 'critical habitat limiting period' (bottlenecks) approach. In France, a dynamic fish population model for brown trout (MODYPOP) has been developed to evaluate trout populations under various river management (flow) schemes (Capra et al., 2003; Sabaton et al., 1997).

Continuous Under Threshold (CUT) Habitat Duration Curves

There has long been recognition that there is a need to develop habitat evaluation procedures that integrate not only time, but the magnitude and duration in habitat availability and the factors (e.g. flows) that influence this variability (Capra et al. 1995). Capra et al. (1995) have expanded on this concept by developing an approach, the continuous under threshold (CUT) habitat duration curve, to look at both the timing and magnitude in physical habitat variations. This concept involves using the results of a habitat time series to generate habitat duration curves, that is the duration (days) in which the WUA is greater than or equivalent to a pre-determined threshold in WUA. The CUT approach then determines continuous durations in which the available habitat (WUA) in a river is less than a given threshold, based on the assumption that there are durations/thresholds which could potentially represent limiting events/periods (i.e. 'bottlenecks') for fish populations. This method can be used to illustrate both short term (days or months during the spawning period) and long term (years, extended droughts) habitat limiting events.

MesoHABSIM

Many researchers have advocated modeling at the meso-habitat scale and Parasiewicz (2002) has developed an approach entitled MesoHABSIM to apply physical habitat modeling on a whole river/watershed scale. This approach involves mapping the river system, in its entirety, at the meso habitat scale (i.e. in different 'patches' or hydro-morphological units), in a hierarchical approach (river, reach, habitat unit). Standard transect based or other means of measuring hydraulic data are then collected from randomly selected habitat units, in proportion to their abundance in the river/reach. Quantitative distribution of depth, velocity (mean or at points in the water column), substrate, along with secondary attributes (min./max., mean, variance, Froude number) are used to describe the meso-habitat. Biological criteria are also meso-habitat based and can be developed for individual species or fish communities, will consider fish presence/absence in different habitat units, or can be defined by the normalized habitat suitability index as per PHABSIM. This has led to the development of the Probabilistic Habitat Index (PHI) for use in MesoHABSIM. The resulting analyses can quantify the probability of habitat area at different flows, can be used to summarize the total or reach/segment based WUAs, or can be subject to different analytical approaches relevant to the larger scale (e.g. landscape metrics). The strength in this approach is the flexibility in scale of analyses and the possibility for cross-scale analyses, efficiency in development of biological criteria for complex fish communities, and the assessment on the scale the aquatic fish community for an entire watershed. Essentially, detailed characterization of a few sites as used in microhabitat modeling is replaced by meso-habitat mapping of the whole river and the precision of hydraulic sampling is adjusted to studying larger units throughout the system.

Mesohabitat (reach) based approaches have also been explored by several other researchers. Multivariate regression is used to develop fish probability of occurrence models based on frequency of occurrence of physical habitat variables at a reach scale (e.g. Lamouroux et al. 1999). A composite suitability index is derived for each reach and then totaled based on the distribution of similar reaches through a longer river segment (e.g. tributary, or the entire catchment).

Statistical Hydraulic and Habitat Models

A conceptual framework has been developed for the coupling of statistical hydraulic models to similar habitat models (e.g. Lamouroux et al. 1999, Lamouroux and Souchon 2002). The hydraulic models are built on statistical distributions of hydraulic features (depth, velocity, shear stress) are linked to habitat models (e.g. fish community structure, biomass) developed at the same scale (e.g. for river reaches). These methods are currently under development but do offer some potential for 'up-scaling' micro and meso-habitat based approaches. Statistically based river hydraulic models estimate the frequency distribution of important hydraulic variables based on simple inputs such as mean river velocity, depth, and width (Lamouroux et al. 1995). Depth or width to discharge relationships are linked to hydraulic distributions over a range in discharge or across a variety of streams with different catchment areas, topographies, etc. These types of models appear to most applicable to analyzing large scale trends in habitat hydraulics, rather than at a reach specific application (i.e. impact analyses).

New Technologies for Data Collection and Analyses

There is considerable emphasis on the application of many current state of the art technologies in data acquisition using remote sensing technologies (Parasiewicz 1996). These include multi-spectral aerial videography, micro-photogrammetry, satellite and airborne imagery, LIDAR and other new tools, as well as new methods for rapid collection of depth and velocity data (e.g. acoustic Doppler current profilers), all of which permit rapid collection of large quantities of data and allow for higher resolution mapping of hydraulic units (Hardy and Addley 2003, Harby et al. 2004). A major improvement provided by these technologies is the concurrent and integrated ability to collect data in time (synchronized time stamp) and space (differentially corrected GPS). There are equally a large number of developments in application of GIS technology to integrate these large, multi-layered data sets, specifically detailed digital terrain modeling (DTM), to characterize hydrodynamic features (e.g. longitudinal gradients, lateral slopes, and even prediction of meso-habitat distributions). This has permitted the ability to collect data, and conduct analyses, for physical habitat modeling to much larger river segments and watersheds (i.e. up-scaling). As new metrics are integrated into modeling regimes, methods to measure these metrics must be advanced (e.g. shear stress, FST hemispheres). Hardy (1998), Hardy and Addley (2003), and Harby et al. (2004) provide a good overview of the technological developments in aquatic resource assessments.

REVIEW OF PRACTICES CURRENTLY IN USE IN CANADA

Newfoundland and Labrador

Newfoundland has recently developed a three tiered approach to specifying stream flow requirements, which is a follow up three year (1994-1997) project to evaluate instream flow assessment methodologies and fish habitat evaluation tools in Newfoundland, conducted under the Green Plan – Habitat Action Plan and the Canada-Newfoundland Agreement Respecting Water Resource Management. This three tiered approach uses a matrix that includes: (i) project complexity, (ii) resource value, and (iii) level of impact on flow, each ranked as high, medium, and low, to determine the appropriate approach for instream flow assessment. The method develops a numerical ranking to recommend whether a subjective evaluation (professional judgement), standard setting (Tennant's, Wetted Perimeter), or more sophisticated, incremental habitat hydraulic simulation (IFIM, PHABSIM) would be the preferred approach to prescribe a modified flow regime. This approach is currently undergoing public consultation and has not formally been implemented at this time.

Until the development of the above 'regional approach' for the selection of methodologies for instream flow assessment, the choice of technique has been on a project by project, ad hoc basis. Tennant's standard setting approach has been used to establish flow release requirements for a major hydroelectric development in 1980 (Upper Salmon Hydroelectric Development), modified to require different flow conditions at different times of the year (i.e. 40% of the mean annual flow [MAF] during the summer and 20% of the MAF in winter; Scruton and Ledrew 1996). On another project (Hinds Lake Hydroelectric Development), regulated flows for Goose Brook were prescribed at 30% MAF over the entire year, although initial recommendations were for higher flows with seasonal variation (60% MAF for summer flows and 40% MAF during winter). Tennant's approach (% of MAF) was also used to establish flow requirements for habitat maintenance and fish migration on the Exploits River resulting in multi-faceted flow agreement for the watershed (Exploits River Flow Agreement, Goosney, Scruton, and Bourgeois, 1992). A unique aspect for this flow regimen was a release of 85% MAF in the spring to facilitate out migration of Atlantic salmon smolts.

The Wetted Perimeter Method (WPM) has not been widely used in Newfoundland although there is anecdotal evidence that flows for Grey River and White Bear River, as part of the Bay d'Espoir Hydroelectric project, were in part established on the basis of some consideration of wetted perimeter (Jacques Whitford Environment et al. 1996). The WMP was also applied to develop a flow recommendation for the Rose Blanche River (Newfoundland Power); however the negotiated flow release did not use the results of the WPN assessment.

A PHABSIM approach was used to investigate flow release requirements for migration of anadromous fish in relation to water extraction for a water supply in 1985 (Shoal Harbour River). The results of the PHABSIM analysis however were not used extensively in negotiating water releases as subterranean flow invalidated the use of the hydraulic model. As part of a federal-provincial study to evaluate the applicability of instream flow assessment methodologies in Newfoundland (Jacques Whitford Environment et al. 1997; Gosse et al. 2001), the three types of assessment tools (Tennant's – hydrological index method; Wetted Perimeter Method-hydraulic rating method; PHABSIM – habitat preference method) were applied to three rivers in Newfoundland, representative of different hydrological characteristics (Jacques Whitford Environment et al. 1996a, 1996b, and 1996c). This was largely an academic exercise for two rivers (Pinchgut Brook, North Arm River), however, the comparative assessment of the three methods was applied on the regulated West Salmon River, in part, to assess the adequacy of the existing flow regime in a retrospective sense (Scruton and LeDrew 1996).

Maritimes

Flow requirements in the Maritime Provinces (New Brunswick, Nova Scotia, Price Edward Island) are defined by the monthly mean flows and a variation of the Tennant approach, requiring 25% of the mean annual flow (MAF) to be retained (Caissie and El-Jabi 1995). The median monthly flow method, or Q50, has also been applied in Atlantic Canada and is considered regionally relevant as it was developed for rivers in the New England states (USFWS 1981). The Aquatic Base Flow method has been examined and Caissie and El-Jabi (1995) found comparable results between the ABF and 25% MAF, suggesting that owing to the higher spatial variability in the ABF estimates, the 25% MAF would be preferable for setting region-wide flow targets.

One example of an instream flow needs assessment in the Maritimes was for the Cheticamp River, Cape Breton Island, Nova Scotia which was regulated as a result of the Wreck Cove Hydroelectric development in 1978 (Triton Env. Cons. 1994). The flow recommendation was determined by flow duration analysis and depth criteria for juvenile Atlantic salmon which required flow augmentation for the summer (July/August) period. A subsequent assessment, based on juvenile fish populations and angling data suggested the fish populations were being maintained by the flow release (Ruggles 1988).

Quebec

In Quebec, an ecohydrological approach has been developed which adopts a hydroecological regionalization approach, that is to say that instream flow hydrological requirements are established according to fish species distributions and communities in different regions of the province (Belzile et al. 2003). Flow requirements are seasonalized, being defined by the critical life stage requirements for targeted species. The method is inspired by standard regionalization methods in statistical hydrology and considers broad aspects of watershed geomorphology (catchment area, % forest cover, gradient, altitude, rainfall, % lakes and wetlands, etc.) to regionalize conservation flow variables through multivariate regression. Target fish species (n=17) were established and Quebec was divided into 10 ecological regions based on watershed boundaries, fish species distributions, and administrative (political) boundaries. Critical biological periods, corresponding to climatic seasons, were identified. A suite of hydrological methods were examined and 4 methods (Tennant's Method, a variation of the New England Method [Q50, September], the Maritimes Method [25% MAF, Caissie and el-Jabi 1995], and statistics based on description of drought conditions ([7Q2, 7Q10, and 10Q5]) were selected for the analyses. This approach has been applied to five pre-project assessments for small hydro development and has been used in ten environmental assessments of water withdrawal projects (Belzile et al. 2003).

Ontario (contributed by Greg Pope, Ontario Power Generation)

Until recently, Ontario utilities and regulators have relied primarily on professional judgement to assess the effects of hydroelectric operations on fish and fish habitat. Ontario Hydro has historically used fairly simple methodologies to investigate existing flow regimes in Ontario, often relying on the ability to control flows with a given generating station and/or spillway. In some instances operations may be observed over a period of time to determine effects on habitat over a range of seasonal flows. Specific flows (using some flow setting methodology) may be set for a particular generating station or dam, often related to the performance constraints of the station. Direct observations may be supplemented by installing flow and water level gauges at strategic locations upstream and downstream from the facility.

For example at one reservoir, the relationship between reservoir elevation and the submergence of potential fish spawning shoals in the spring was determined by monitoring headwater elevations over a number of weeks while the reservoir was filled. The study provided information to the operators on how rapidly the reservoir must be filled to provide access to specific shoals for spring spawning species. In another case, flow setting was employed at a generating station to study the peaking operation on the river. Over a 1 week period, river elevations and down-ramping rates were determined for a decreasing number of operating units. Observations were made at a number of locations downstream including known spawning areas for brook trout by fish biologists and by using continuously recording water level gauges. Simple models were produced for specific downstream areas relating river elevation to the number of units operating and showing the rate of decline of elevation after a decrease in flow. Studies in Ontario have tended to focus on a small number of valued sport and commercial fish species including walleye, northern pike, lake trout, brook trout, lake whitefish and lake sturgeon. More sophisticated habitat modeling has probably not been utilized because models such as PHABSIM are not particularly suited to these species (i.e. non-salmonids) and to the large Ontario rivers on which hydroelectric stations usually occur.

Recently, the Ontario Government has modified existing legislation (The Rivers and Lakes Improvement Act) to require utilities to prepare Water Management Plans (WMPs) for all rivers wholly within Ontario boundaries, with hydroelectric facilities, by March 31, 2004. Water Management Plans will attempt to maximize the net environmental, social and economic benefits of waterpower operations, and should, at a minimum, arrest any on-going degradation of riverine ecosystems. Water Management Plans will consider a variety of uses and needs including hydroelectric power generation, public safety, flood management, fisheries, wildlife, recreation, navigation, erosion, First Nation values, cultural heritage, economics and the natural flow regime.

The natural flow regime approach is an Ontario Ministry of Natural Resources' concept heavily influenced by American researchers such as Poff (Poff et all 1997). Ontario Ministry of Natural Resources describes the natural flow regime as a framework to achieve an ecosystem approach in water management planning, and to enable issues and objectives to be addressed at a broad scale. To provide guidance in its application, Ontario Ministry of Natural Resources has developed the Aquatic Ecosystem Guidelines (AEGs) for Water Management Planning.

Under Water Management Planning, the OMNR has proposed new methodologies and tools to investigate the original natural flow regime at hydroelectric sites. The baseline aquatic conditions are the conditions and characteristics of the aquatic ecosystem at the time water management planning commences. The AEGs require that consideration be given to moving the flow regime back towards a more natural condition. For rivers, emphasis is placed on low flow conditions, bank full flows, riparian flows, and ramping rates; for reservoirs, emphasis is on winter drawdown and summer water level fluctuations.

Ontario Ministry of Natural Resources uses the existing historical daily flow data for each hydroelectric facility on the river for the period 1973 to 2002 (30 yrs) to simulate the annual, seasonal and monthly natural flow regime. To facilitate this, Ontario Ministry of Natural Resources uses the Ontario Flow Assessment Techniques (OFAT) based on a number of existing regional hydrologic models for Ontario supported by GIS to provide various physiographic and climate inputs to the models. Various analyses, including streamflow time series, flow duration, flood frequency, low flow frequency and rate of change analysis are used to calculate a number of target metrics as described in the AEGs and the Waterpower Science Strategy (Ontario Ministry of Natural Resources 2002). Final decisions have not been made on selection of the metrics, but at this time, MNR appears to favour adoption of the 80 % time exceeded metric calculated on a monthly basis as a target for minimum flow, bank full flow and riparian flow in rivers. Currently, the Ontario power industry is proceeding cautiously in the application of this approach since the concept is largely theoretical, there is little science available from Canada to apply to the approach, and the benefits are vague. To support Water Management Planning, Ontario Ministry of Natural Resources has also initiated several research projects through the development and implementation of the Waterpower Science Strategy (WPSS).

Prairie Provinces

Alberta historically utilized a two tiered system, with the Tessman method (monthly modification of the Tennant approach) used for level I assessments, requiring a decision over a short time frame or where significant fisheries resources are not present (Locke, as cited in Dunbar et al. 1998). For level II assessments, the IFIM, incorporating physical habitat simulation and water quality models, has been used for a variety of reasons (e.g. hydroelectric development, water extraction for irrigation), under both agency driven studies and studies related to environmental assessments. Standard PHABSIM analyses is used to generate WUA versus discharge relationships for target species/life stages and these are divided into Biologically Significant Periods (BSPs), based on professional judgment and a composite habitat discharge relationship, defined as a Fish Rule Curve (FRC) is developed for each BSP. Minimum flows are then recommended from an examination of the FRC for inflection points or based on 80% of the optimum flow, or the 80% exceedence percentile. ‘Average’ flows are similarly defined as 50% of the optimum flow or the 85% exceedence percentile. These values can be assessed for ‘average’, ‘dry’, and ‘wet’ years.

Alberta has recognized that much of the cost associated with instream flow assessments has been related to development of fish habitat criteria and have focused on the issue of transferability. Generally, transferability attempts have been unsuccessful and a numbers of reasons have been advanced for failure (fish are generally distributed w.r.t. habitats, habitats are not limiting, etc.). It has been suggested that generalized habitat suitability criteria could/should be developed by the ‘expert panel’ approach (Delphi) with a view towards wide application at the expense of river specificity. Considerable effort has been devoted to the development and refinement of the River2D model, and on development, testing and application of habitat suitability criteria, including innovative meso-habitat based approaches ('spatial niche analysis'), focused on the Kananaskis River (Katopodis 2003; Christison, et. al. 1999). Alberta has also undertaken a Stream Classification Scheme, which is viewed as a first step ('standard setting') in characterizing hydrological characteristics of river basins.

In Saskatchewan, 'standard setting' approaches, including the Tennant and the Tessman models have been historically used for instream flow assessments (Rob Wallace, Saskatchewan Department of Environment and Resource Management, presentation to the DFO Habitat Suitability Criteria Workshop, Burlington, ON, November 2000). Recently, there has been more widespread application of a habitat modeling approach, utilizing the River2D hydraulic model, particularly for large inter-Provincial river basins (e.g. the Assiniboine River, North and South Saskatchewan Rivers).

In Manitoba, an IFIM approach to instream flow assessment has been adopted using a either, or a combination of, PHABSIM and River2D approaches and river specific, as well as transferred, habitat suitability criteria (Joel Hunt, Manitoba Department of , presentation to the DFO Habitat Suitability Criteria Workshop, Burlington, ON, November 2000). Work has been undertaken by DFO (Bill Franzin, presentation to the DFO Habitat Suitability Criteria Workshop, Burlington, ON, November 2000) to integrate the scale of fish habitat utilization (local to watershed), adopt a more community based approach, and to investigate instream flow assessment approaches for very low gradient (slope) rivers in the Prairies. Work has focused on broadening and 'operationalizing' the EDT (Erosion, Deposition, Transportation) concept towards development of an integrated aquatic habitat classification (AHC) scheme that could be applied equally to lakes and streams using these basic mechanisms.

Recently, the University of Alberta, DFO, and the Alberta Department of the Environment have advanced the development and application of River2D, a 2-dimensional, depth averaged, finite element, habitat hydraulic simulation model and have applied the model to the instream flow analyses of a variety of Canadian Prairie rivers (Katopodis 2003). This model's framework is very similar to the IFIM concept, and utilizes similar biological suitability criteria, resulting in discharge versus habitat area simulations. The model was applied to the assessment of fish habitat and recreational opportunities on the Kananaskis River under hydro peaking conditions. This assessment utilized 2-D modeling coupled to time series analysis (WinHabTime, Utah Sate University) to simulate 'effective habitat' for fish life stage defined Biologically Significant Periods (BSPs) for a variety of operational scenarios. A recent innovation in the River2D model is in relation to the simulation under ice covered conditions and is currently applied to the development of a science based winter environmental flow for the Athabasca River. This model is available on the web (www.river2d.ca) and has been used for studies in other parts of Canada, the U.S.A. and elsewhere. Further development, refinement, and application of this model is ongoing.

British Columbia (contributed by Mike Bradford, DFO, and Hugh Smith, BC Hydro)

A Water Use Planning process for British Columbia was developed in 1998 in response to increasing demands on the province's water resources. The overall goal was to find a better balance between competing uses of water such as domestic water supply, fish and wildlife, recreation, heritage and electrical power needs that were environmentally, socially and economically acceptable to British Columbians. Over a five year period, Water Use Plans are in the process of being completed for all of BC Hydro's hydroelectric facilities through a consultative planning process. Currently, BC Hydro is close to having completed Water Use Plans for 30 BC Hydro facilities operating on 27 watersheds, through 22 separate water use plans.

Plans are based on a Federal/Provincial agreement and a set of Provincial guidelines. Currently, no other utilities in BC have been involved in the process and BC Hydro voluntarily opened their licenses for review. To date, BC Hydro has completed 18 public reviews and have gained operational consensus on 17. The remaining public reviews will be completed in fall 2004. The driver for BC Hydro has been to gain agreement on the best operations to satisfy the multitude of expectations from our facilities. Alternative processes, while satisfying some stakeholders, were not able to satisfy the need to make trade-offs between resource interests.

The process involves open dialogue with all stakeholders, regulators and First Nation to determine; issues, objectives, performance measures, data collection/research needs, definition of alternative operating scenarios, and finally development of an integrated resource management decision process to determine the best overall alternative. Those involved in developing a water use plan will assess competing alternatives and address these interests to create recommendations for water management at BC Hydro facilities. Each water use plan, once authorized under British Columbia's *Water Act* will set the conditions for the operation for each licensed facility. The plan will also be reviewed by the DFO who may provide authorizations, as appropriate.

Recently, the BC Ministry of Water, Land and Air Protection (MWLAP), BC Ministry of Sustainable Resource Management (MSRM), Land and Water BC Inc. (LWBC), and DFO have developed the British Columbia Instream Flow Guidelines for Fish which have established a two-tiered review process to assist in setting instream flows in British Columbia streams. The Guidelines are made up of two main components, Flow Thresholds, and Assessment Methods. The first tier is a scoping level process that provides seasonally-adjusted thresholds for alterations to natural stream flows that are expected to result in low risk to fish, fish habitat, and productive capacity. These thresholds are a "coarse filter" for review of proposed water uses where little or no biological or physical data are available. Alternatively, good quality data may indicate that it is safe to undertake water diversions in excess of the thresholds. Projects that exceed these flow thresholds must collect additional data, which will be reviewed and assessed during a more detailed project review (tier 2). The Assessment

Methods are a set of endorsed techniques for assessing flow alterations and concentrate on techniques for collecting data used during more intensive project reviews. More detail on these guidelines and techniques are found in Hatfield et al. (2003) and Lewis et al. (2003).

The North

Various, mostly desktop methods, have been used in northern Canada for a variety of projects. Lack of hydrological, hydraulic and biological data is particularly severe in the tundra area of the north, where diamond mining is located. The River2D model was used in a study of the effectiveness of a constructed channel, the Panda Diversion, in replacing stream habitat affected by Ekati, the first Canadian diamond mine (Jones et. al. 2003; Smith et. al. 2002).

KNOWLEDGE GAPS AND RESEARCH NEEDS

Frameworks and Scale

Within Canada, and particularly in the context of the mandate and responsibilities of the DFO and CEA, there is a need for development of a comprehensive framework for assessment of flow related alterations on fish and fish habitat to include planning level approaches, simple index methods, and complex habitat hydraulic modeling approaches. The framework should consider and integrate existing assessment approaches currently in use in the Provinces (e.g. water management agencies) and by various utilities, and, where possible integrate existing tools used to assess flow management for hydro schemes. Integrated management and development of water resources requires harmonized and comparable protocols, techniques, and tools all oriented from a reach to catchment scale (Harby et al. 2004). This would need to include establishing the appropriate justification, standards and setting criteria that are ecologically based and incorporate regional differences in ecology, climate, geomorphological conditions, and socio-political settings. The ‘eco-hydrological’ approach developed for Quebec (Berube et al. 2003) and the current Watershed Planning Process in Ontario and British Columbia are good examples of ‘new thinking’ in setting regional objectives, however these concepts need to be broadened for national application. At a planning level, Caissie and El-Jabi (2003) suggested more research is required in relation to standard setting techniques such as determining the basic relationship between habitat and MAF on a regional basis, and that MAF could become a good benchmark for broader watershed planning as it is easily related to local hydrology (i.e. water availability).

Within this framework, there needs to be consideration of appropriate spatial and temporal scales for habitat modeling and mechanisms for up-scaling habitat simulations to river reaches, watersheds, and for multi-species fish communities. There is a need for improved integration and application of the various tools and techniques, currently in use and under development, to the appropriate scale of assessment. For example, the application of micro-habitat based models has been demonstrated to be inappropriate to the assessment of development of large, mega project schemes. These types of assessments would need to consider the relevance of habitat features across a range of scales and may benefit from the development and inclusion of new metrics that can describe habitat quality at a variety of scales (e.g. landscape ecology theory). Any over arching framework must also consider that model development, application and refinement is an ongoing process and assessment approaches must be flexible and adaptable to accommodate new thinking.

Natural Flow Paradigm

In most developed nations, it is widely recognized there is a need to consider flow management (regulation) within the context of a 'natural flow paradigm' or mimicking natural river systems. More research is required into determining what components of a natural flow regime, and what magnitude of flow volumes, would be necessary to maintain the essential ecological character of a river while permitting some degree of modification and /or regulation. Development of future regulated flow regimes, or modification of existing regimens, need to integrate some elements of temporal variability in flow to address geo-morphological and biological considerations. A major consideration would be in relation to the high (peak) flow requirements for channel maintenance, sediment flushing, and for key biological life stages (e.g. downstream migrants) as this will be a key factor in the feasibility of water development schemes.

Application to Range of Development Types/Scales

Most habitat-hydraulic models currently in use have been developed from studies on small (wadable) to medium sized rivers and for large hydroelectric projects where there is sufficient water storage to modify (low and high) peak flow conditions. Modeling approaches also must be adapted and/or developed for prescribing flows for small 'run-of-the-river' and peaking hydro schemes, or equally for very large hydro developments (need tools for 'up-scaling' or development of completely innovative methodologies). Models also need to be broad in application to a wider variety of rivers types (e.g. low slope rivers in the Prairies, high gradient rivers).

Currently there is a need for further research into the fundamental impacts of 'run-of-the-river' and 'hydro peaking' regimes on aquatic resources. These would include: (i) effect of rate of change (ramping rate) on fish species, habitat, benthic communities and drift; (ii) effects of changes under seasonally variable conditions, with a focus on winter; (iii) behavioural and physiological effects on fish and resultant effects on populations; and (iv) ecosystem (all trophic levels) effects manifested in fish populations (Steel and Smokorowski 2000).

Monitoring/Validation/Adaptive Management

One of the most promising avenues to conduct research into effects of hydroelectric development and flow management is to conduct rigorous, scientific, effects monitoring studies to validate the effectiveness of the flow prescriptions, to permit fine-tuning and modification, where required in an adaptive management context, and to contribute to the knowledge base upon which future flow modification decisions are based. This would require development of approaches for meaningful biological effects monitoring and adaptive management into the assessment, development, and evaluation of regulated flow regimens. A particularly effective tool in this regard may be adaptive management approaches that would modify flow regimes based on monitoring results and then continue to evaluate biological responses. Some authors have suggested that monitoring approaches should adopt a complimentary holistic approach, to single species assessment, such as an Index of Biotic Integrity approach (Leclerc et al. 2003). This would be particularly relevant to large rivers, complex fish communities, and possibly for pre- (river) and post- (impoundment) comparisons.

Effects monitoring studies could be conducted in a validation context, assessing the outcome of recommended flow regimes, and this could be through a variety of approaches and scales including: (i) studies relating fish presence/absence to habitat suitability; (ii) studies relating a model predictor (e.g. WUA) with a biological indicator (e.g. fish abundance): (ii) or longer term studies looking at the health of fish populations and/or communities. Further, effects monitoring and/or validation studies could address some of the assumptions or uncertainties associated with the modeling and assessment process. Most authors (e.g. Leclerc et al 2003) have suggested validation strategies move away from the simple comparison of WUA and fish production (biomass) towards validation of habitat preferences, or in quantifying the uncertainty associated with preference functions and/or models.

Tool Development

Despite the current state of the science in flow assessment methodologies, there is a need to continued development, testing and refinement of habitat hydraulic modeling tools with particular emphasis on biological models and methods to integrate effects at a fish population/community level (Wesche and Rechard 1980; Harby et al. 2004). Future research should also consider development of new methodologies and metrics to describe habitat quality and quantity, in the context of 'habitat productive capacity' surrogates (DFO mandate). Many researchers have suggested increased use of multivariate statistical approaches to permit assessments to move beyond the micro and meso-habitat scales (reaches, watersheds). Approaches need to be pursued to more fully integrate all aspects of river management in the context of 'ecologically integrated' flow management (see below). Several authors (e.g. Leclerc et al. 2003, Morin et al. 2003) have stressed the need to include additional physical habitat parameters in the models such as water temperature, available light within the water column, organic matter, turbidity, etc., particularly when applied to large river environments.

There needs to be consideration of the accuracy and intensity of spatial sampling needs for habitat quantification, since fish select habitat at a fine scale, and current technologies may lack sufficient measurement resolution and modeling precision to capture these relationships. While it is apparent there have been considerable advances in the capabilities of hydraulic simulation tools (2 and 3-D), additional development is necessary to overcome shortcomings on modeling riparian areas, applicability to rivers with high bed roughness at low flows, river flow interaction with ground water and, in particular, for consideration of ice regimes (Katopodis 2002; 2003). A major need for Canada, and other cold northern locales, is major advances in hydraulic simulation models to be applicable to under-ice conditions. Any increased resolution of hydraulic simulations will only be beneficial if there is concurrent development in 'meaningful' biological models to exploit this information.

There have been a variety of avenues pursued in habitat modeling such as landscape theory, ordination techniques, gradient analyses, artificial neural networks, 'fuzzy rule' preference functions, decision trees, etc., however these developments must be considered exploratory and largely of academic interest at this stage, with some limitations for potential utility to the applied science of habitat-hydraulic modeling.

Biological Modeling

Habitat models have provided a robust repeatable and understandable means appreciating the ecological effects of flow regulation; however most researchers and practitioners feel that the largest need to advance the science of habitat-hydraulic modeling is in the area of the biological models and their components (Harby et al. 2004). Many agencies have recommended research into the underlying principles and assumptions of habitat preference methods and more work in model validation, from both a physical and biological perspective (e.g. Reiser et al. 1989). Models, and biological criteria, must reflect temporal (seasonal, diel) and spatial scales of habitat preference, explicitly consider the inter-dependence among habitat attributes, and need to be integrated across life stages and species to reflect a life history and/or population based approach to evaluation of flow related effects (Orth 1987). Population based approaches may be able to integrate the effect of a variety of biological processes without understanding the mechanics behind the processes. Time series techniques need to be developed to assess potential flow related limitations in microhabitat availability that may constrain or regulate key life stages and populations, or be critical to survival ('habitat bottlenecks'). Methods must recognize that with river fish populations, there are likely inter-relationships between recruitment limiting situations and carrying capacity limitations over time. These also lead to more consideration of inter- and intra-specific relationships (territoriality, competition, predation, niche overlap, migration, food availability etc.) in habitat modeling processes. Some of the important interactions that are not currently considered include spatial links between habitat types (patches), relationships of habitat preference and tolerance, metabolism, effects of disturbances and long term variability, interactions with terrestrial ecosystems, and the direct or indirect effect of human interventions (e.g. fish stocking, angling).

Generally, despite many years of research, there is insufficient basic knowledge of life history requirements of all target species and variable life history strategies between different populations in different regions, and the structuring of what knowledge is available for use in the habitat hydraulic process. For many species, habitat modeling for small, juvenile (0+) fish needs further development (Parasiewicz and Dunbar 1998). For the most part, most of the modeling emphasis has been initially been on salmonid species and there is a major need to develop the appropriate biological models to support instream flow tools for economically and ecologically important non-salmonid species. This is particularly important for species identified as threatened or endangered under the new Species at Risk Act (SARA).

Other Trophic Levels

In the context of adopting a more holistic and ecosystem based approach to flow regulation, there is an urgent need for integration of broader ecological criteria and inclusion of 'non-fishy' considerations into the analyses. These could include consideration of such elements as macro benthos, from both the perspective of indicators of ecosystem health and as fish food, and aquatic plants, also both the perspective of an important part of the ecosystem and as elements of fish habitat.

These other ecological factors may affect fish as, for example, food availability (e.g., invertebrates or forage species) is often identified as a major limiting factor which may only in part be determined by hydraulic conditions.

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TABLES

Table 1. Instream flow regimes for fish, wildlife, recreation, and related environmental resources (from Tennant 1976)

[1]Narrative Description of Flows	Recommended Base Flow[2] Regimen Percent of Mean Annual Flow	
	October to March	April to September
Flushing (maximum)	200	200
Optimum	60-100	60-10
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	20	30
Poor	10	10
Severe Degradation	< 10	< 10

Notes:

- [1] Most appropriate description of the general condition of the streamflow for the parameters listed in the Table caption.
- [2] Tennant's term presumed to mean lowest fixed flow, not a hydrological term.

Table 2. Habitat hydraulic modeling frameworks for assessing flow modification (adapted from Parasiewicz and Dunbar 2001).

Name (Acronym)	Description	Reference(s)
IFIM (Instream Flow Incremental Methodology)	Framework for integration of ecological demands into the water resource planning process	Bovee (1995)
PHABSIM (Physical HABitat SIMulation system)	The original physical microhabitat simulation model for use within the IFIM framework	Bovee (1982)
RHABSIM (Riverine HABitat SIMulation)	A commercial software program incorporating the PHABSIM	Payne (1994)
RYHABSIM (River hYdraulic and HABitat SIMulation)	A microhabitat based model for New Zealand, similar to PHABSIM	Jowett (1989)
EVHA (EValuation de HAbitat)	A French microhabitat based model, similar to PHABSIM	Ginot (1995)
RSS (River System Simulator)	A Norwegian microhabitat model (HABITAT) contained within a riverine modeling framework	Alfedsen and Killingtveit (1996); Killingtveit and Harby (1994)
CASIMIR (Computer Aided SIMulation of habitat In Regulated streams)	A German simulation model based on shear stress for hydroelectric development impact assessment	(Jorde 1996)
HABIOSIM/ HYDREAU	Canadian microhabitat modeling system	Lafleur and LeClerc (1997); Locke (1996)

FRC (Fish Rule Curve)	incorporating PHABSIM and habitat time series analyses	
AGIRE	A GIS based modeling system incorporating various thematic temporal and spatial data.	
RCHARC (Riverine Community Habitat Assessment and Restoration Concept)	A modeling system comparing the habitat hydraulic conditions between a reference situation and alternatives.	Nestler et al. (1996)

SUMMARY OF GROUP DISCUSSION FOLLOWING PRESENTATION

Dave Scruton's presentation of this paper gave an overview of the state of knowledge pertaining to the effects of flow modification on fish and fish habitat. Following the presentation, the participants were encouraged to identify and discuss issues of relevance for Flow Modification, particularly as they related to future research needs. A number of points and suggestions were identified.

- Resource material available from Committee on River Ice Processes and the Environment; some modeling has been done based on what is known.
- Develop a matrix/comprehensive framework to show connection between methods and objectives. Has implications for research agenda and Interpretation Bulletins.
- Develop framework to account for uncertainty.
- Gap exists in geomorphology; need to understand river responses, stability, and impact on ecosystems.
- Determine what is more appropriate -- more fitness or more robustness of models. Need ability to determine how predictions will be upheld/falsified.
- Gap exists in how information id applied to the practical requirements of Hydro operations; resolution would be helpful for species at risk.
- Criticalness of monitoring identified.
- Determine whether a methodology exists that could be applied to both new and existing facilities. No set approach currently.
- Identify the breakdown between new versus existing facilities.

This input was quite helpful for the prioritization of future research in Flow Modification.

A review of the State of the Science, Knowledge Gaps, and Research Priorities for Fisheries and Oceans Canada and the Canadian Electricity Association – Reservoir Creation and Operation

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ABSTRACT

To further the objective of achieving a research agenda on fish, fish habitat, and hydro electricity generation, a working group, composed of DFO and hydro industry experts, was established to conduct a state of the knowledge analysis related to hydroelectric reservoirs. The analysis included a literature review summary of existing knowledge, an assessment of knowledge gaps, and provision of research recommendations. Summaries of ongoing research which would address some of the identified knowledge gaps were provided. Topics covered include the impacts of reservoir creation and operation on habitat, biological productivity, fish communities, mercury in fish, and an assessment of measures known to mitigate effects. The first recommendation was to conduct a data mining and reporting exercise to assess the potentially vast sources of information available from industry, consultants, and government agencies across the country. In addition, where warranted, it was recommended to develop a collaborative, well designed, multidisciplinary research program in an adaptive management framework to address outstanding knowledge gaps where changes in operational regimes of reservoirs are set to occur.

EXISTING KNOWLEDGE

Reservoir Creation

Habitat Modification

Most of the studies addressing the issue of the thermal effects of reservoir creation are related to downstream effects of reservoir and generating stations, and few concern the thermal regime in the reservoirs compared to natural lakes or rivers. When percentage increase in surface area and volume is of low amplitude, impoundment would have no obvious effect on vertical thermal distribution (Bodaly et al 1984a). On the other hand, the rise in water level can result in cooler water temperatures (Strange et al 1991). In large reservoirs, thermal inertia causes a delay in freezing and thawing and cooling of surface water during the summer period (Therrien et al 2002).

The main impact on thermal regime is likely downstream of power dams. Hydro dams can have an effect on the downstream temperature regime (Spence and Hynes 1971) and the impact can persist for a distance of several km below the dam, but decline further downstream (Webb and Walling 1993). Water temperature below dams and generating stations are cooler, which may cause changes in fish communities (Therrien et al 2002) and attract cold water fish downstream (Barnes and Bodaly 1994).

Change in water quality and nutrient dynamics is one of the aspects which has been given much attention. Following impoundment there is a trophic upsurge which has been described in several instances. The decomposition of organic matter contained in the flooded soils and vegetation causes a release of nutrients such as phosphorous. The fate of inundated vegetation and its effect of water quality and nutrients is discussed in Ploskey (1985). This upsurge translates in primary production, and makes its way up the food chain (Newfoundland and Labrador Hydro 1993). This increase is temporary and after several years, the changes are virtually over (Grimard and Jones 1982, Schetagne 1994). In the more stagnant areas of the reservoir, peaking occurs later and last longer (Therien and Morrison 1984).The flooded terrestrial area to annual water volume ratio should be a good index of the potential for water quality modification (Schetagne 1994).

Habitat structure and types are generally well described for streams, but little attention has been devoted to describe habitat types in reservoirs. Reservoirs occupy an intermediate position between rivers and natural lakes with regard to 1) morphologic and hydrologic characteristics, 2) the relative importance of external nutrients inputs and internal nutrient cycling, and 3) the significance of allochthonous vs. autochthonous sources of organic matter to the food web (Kimmel et al 1990).

Water exchange time increases as a result of impoundment, because of the increased volume, although changes are very different depending of the different regions of the reservoirs (Hecky and Mc Cullough 1984). The increase in water volume appears to create an environment that favours pelagic species (such as emerald shiner and cisco) over littoral species (such as pike) (Power 1992).

Flooded trees and branches have replaced in reservoirs the macrophytes as growth substrates for the periphyton and shelters or supports for organisms, usually benthic (Roy et al 1986).

In clay deposit zones, erosion of clay material along shorelines can increase sedimentary input and turbidity, persisting for decades (Hecky and Mc Cullough 1984).

Biological Productivity

Biological productivity, at the lower level of the food web, has been studied in several boreal reservoirs. There is a general consensus that ecological processes in reservoirs are very similar to natural lakes. "The physical and resulting biotic structural characteristics of reservoirs are indeed markedly divergent from general properties of natural lake ecosystems. Nonetheless, upon careful scrutiny I reach the overriding conclusion that reservoirs are very similar to lakes in terms of basic ecological processes and their controlling factors." (Wetzel 1990).

Multiple-year data that permit evaluation of year-to-year variability in lake and reservoir productivity are rare. However, the comparisons that are possible suggest that phytoplankton production in reservoirs is not significantly more variable on an annual basis than is phytoplankton production in natural lakes (Kimmell et al 1990). This suggests that reservoir ecosystems possess a resilience or "dynamic stability" that tends to return them to their previous state in spite of repeated perturbations (Kimmell et al 1990).

The response of primary production to impoundments is highly variable and depends on specific conditions within the manipulated ecosystems. The classical response is an upsurge of productivity during flooding followed by a decline to pre-impoundment levels after a few years (Bodaly et al 1984a, Ostrosfsky and Duthie 1978, Schetagne 1994, Therrien et al 2002). Most new impoundments experience an increase in plankton biomass which is indicative of an increase in biological production, followed by a phase of reduced productivity (Han and Duthie 1989). In the La Grande complex reservoirs, photosynthetic activity increased progressively until the third year after the onset of the reservoir formation and it maintained itself at that level until the sixth year (Roy et al 1986). Mean rates of primary production after reservoir creation can increase by two and a half times the pre-impoundment rates (Power 1992).

The immediate effect of impoundment of the Churchill Falls project was a decrease in primary production due to increased turbidity and diluted standing crops. The long-term effect was a several fold increase in primary production, increased nutrients, and increased standing crop of phytoplankton. Both phytoplankton and zooplankton populations generally increased and changed qualitatively with impoundment, especially in shallow water (Duthie and Ostrofsky 1975). However, in Cat Arm, there were no increases in either phytoplankton biomass or primary productivity during the first three years of impoundment (Campbell et al 1998).

Zooplankton response differs between reservoirs and among different regions of a given reservoir. After flooding, responses vary from no change in densities or decline (Bodaly et al 1984a, Schetagne 1994), to zooplankton increase by one or two order of magnitudes (Pinel-Alloul and Methot 1984, Ostrofsky 1978).The mean residence time of water has been identified as the most important factor of the abundance and densities of zooplanktonic organisms (Roy et al 1986). In reservoirs, the highest densities and biomasses are measured in bays isolated from the main current and, preferably, protected from strong waves. Following trophic upsurge, there is an increase in zooplankton density and biomass a few years after impoundment. Rotifers predominance after the filling up of the reservoirs may be attributable to their detritical feeding mechanisms. The succession and dominance of microfilter-feeder crustaceans is related to hydrological and trophic factors and can be linked to the maturation process of the new reservoir (Pinel-Alloul and Methot 1984).

Response of benthos to impoundment generally follows trends in primary production. In northern Manitoba, standing crop of macrobenthos increased after flooding and, within 3 years, decreased towards pre-impoundment abundance (Bodaly et al 1984a). The response is rapid and ascribed to additions of nutrients and organic matter from newly flooded land. A high degree of species diversity was maintained and there was no evidence of a succession of macrobenthic taxa due to impoundment (Bodaly et al 1984a). In the Lower Churchill River (Manitoba), benthic standing crop declined after diversion, although in lakes with increased water level, invertebrate standing crops increased due to nutrient addition from the Churchill River (Wiens and Rosenberg 1994).

In Laurel Creek reservoir, from the first filling, colonization of the macroinvertebrate fauna along the margin was an active process which accelerated as water temperature increased. During the second year, the colonization was more rapid as a result of overwintering of many limnophilic species (Paterson and Fernando 1969).

In the La Grande complex, during the first year of flooding and the one that followed, there was a reduction in the number macrobenthic taxa (Roy et al 1986). Organisms relatively mobile and less dependant on dissolved oxygen rapidly colonized new aquatic habitats. However, the presence of numerous substrata on which periphyton had established itself greatly increased the available habitats; that has often allowed higher densities and biomasses at sampling than control stations.

Three oligotrophic reservoirs in Alberta do not support high standing crops or diversity of benthos. Maximum abundance occurs in the vicinity of the drawdown limits rather than in the littoral zone (Fillion 1967). Changes to the downstream benthos resembled those that might be expected to occur following mild organic enrichment (Spence and Hynes 1971).

Changes in fish community

Species composition generally does not change importantly in reservoirs after flooding and depends largely on spawning success (Bodaly et al 1984a, Roy et al 1986, Therrien et al 2002, Therrien and Dussault 2004). For instance, the fish species occurring in Smallwood Reservoir are similar to species assemblages in other lakes of western Labrador and Quebec (Bruce 1984). Relative abundance of species which reproduce in shallow water in autumn, such as lake trout, may decrease because of recruitment problems. On the other hand, species relying on elevated water level in the spring, such as northern pike, may benefit from impoundments. A fish species' response to flooding may be determined by various factors including: recolonization ability, habitat vulnerability, and life history (Pearsons et al 1992). Exotic species introduction by intercatchment water diversions may occur but examples are difficult to find (Rosenberg et al 1997).

Greatest changes in fish composition or relative abundance occur downstream of power dams. Because of decreased water temperature downstream of generating stations and control structure, coldwater species may take advantage over warmwater species (Therrien et al 2002).

Absolute density and biomass estimates are lacking and changes are monitored through catch per unit of effort (CPUE). Long term monitoring programs covering pre-flooding conditions until the reach of equilibrium are rare in Canadian reservoirs. In general, CPUE data do not suggest reduced abundance of fish in reservoirs (Power 1992, Deslandes et al 1995, Therrien et al 2002). In some instances though, CPUE is lower than pre-impoundment mean (Bodaly et al 1984a, 1984b). Declines may be due to major movements of fish out of the reservoir in response to reduced light penetration resulting from shore erosion of clay sediments (Bodaly et al 1984a, 1984b). In other cases, decrease in CPUE was temporary and related to the dilution effect and after several years, they were back to pre-impoundment values (Deslandes et al 1995, Therrien et al 2002).

There is lack of accurate fish biomass estimates, but this would require a major and expensive research effort (Newfoundland and Labrador Hydro 1993).

Growth and condition factor after impoundment generally follows overall productivity trend, i.e. increase during the first year, then a return to pre-flooding levels, although an increase in growth was not always observed. The impoundment of Wumpaw Bay (Southern Indian Lake) had no discernable effect on the growth and condition of pike (Bodaly and Lesack 1984). In Smallwood Reservoir, growth rates are within the range published for northern populations of lake whitefish that are unexploited with most displaying a slow to intermediate growth rate. Lake whitefish in Smallwood Reservoir have a good fishery potential based on the growth and mortality rates (Bruce 1984). However, back-calculated growth rates of lake whitefish showed that whitefish from the more recently flooded lakes were generally faster growing than those from lakes flooded 10 years earlier (Bruce 1984). Growth rate and condition of whitefish increased after impoundment on the La Grande complex (Deslandes et al 1995).

Generally, condition factor of fish increase following creation of reservoir, followed by a return to previous level (Power 1992, Strange et al 1991, Therrien et al 2002). Fish below control structures may be stressed and present low condition factor (Barnes et al 1984).

For many species, the reproductive success in reservoirs is fundamentally dependant on the availability of suitable spawning habitat (Machniac 1975).

There is increased recruitment for several species of fish following impoundment, followed by a return to normal level (Bodaly and Lesack 1984, Deslandes et al 1995, Mutenia 1985, Therrien et al 2002). Fine sediment deposition from wave erosion of clay shore material can lead to low egg survival for some species (Fudge and Bodaly 1984). Fish below control structures may experience reproduction problems (Barnes et al 1984, Curry et al 1994).

Fish production or yield estimate is an area which receives little attention in Canadian reservoirs. When compared to natural lakes, fish yields in reservoirs compare favourably although there might be exceptions. When species which are preadapted to lacustrine conditions are present in reservoir watersheds, these fish colonize the reservoir and occupy all the available area. The fish yields when pelagic and littoral lacustrine fish are present mirror the yields in old lakes where these fishes are indigenous (Fernando and Holcik 1989).

According to Randall et al (1995), fish production in man-made reservoirs is higher than in lakes. Power (1992) concludes that conditions in the Cat Arm Reservoir for fish are probably superior to those in the original lake. In Northern Finland, reservoirs have habitually produced annual increments in catches as a result of strengthening fish stocks and intensified fishing (Mutenia 1985).

In Southern Indian Lake, decline in catch was related to shoreline erosion of clay material, which resulted in movement of fish out of the reservoir, due to reduced light penetration.

Absolute estimates of potential yield are rare for Canadian reservoirs. A long-term potential yield of 2.85 kg/ha/yr was calculated for Smallwood reservoir. It falls within the range published for similar species assemblages in similar temperate environment (Bruce 1984). In US reservoirs, a multiple regression of commercial harvest on mean depth, water-level fluctuation (vertical), storage ratio (reservoir volume divided by average annual discharge), and growing season was significant (R2=0.48) and was one of the most useful equation developed. (Jenkins 1967). Such regression do not seem to exist for Canadian reservoirs and it would certainly be helpful to develop such kinds of models to evaluate the productive capacity of these water bodies, especially in the context of Canada's policy for the management of Fish Habitat (1986).

Mercury in fish

It is now well established that concentrations of mercury in fish in newly flooded reservoirs become elevated above background levels (Bodaly and Fudge 1999; Schetagne and Verdon 1999). Concentrations can rise to quite high levels, especially in boreal reservoirs, where mercury as high as 3 µg/g (w.w.) has been observed in predatory fish (Fig. x), as compared to the Canadian limit for the commercial sale of fish of 0.5 µg/g and the Health and Welfare Canada limit for "continuous consumption" of 0.2 µg/g. Peak concentrations occur within approximately ten years after flooding and gradually decline thereafter. In predatory fish, concentrations can take up to 30 years to return to background levels (Fig. x; Schetagne and Verdon 1999). Although the problem has been well defined in the boreal zone, including Canada and Scandinavia, there has been little research in temperate and tropical areas. The problem seems to be less severe in temperate and tropical areas (e.g. Yingcharoen and Bodaly 1993), perhaps due to higher levels of productivity.

The cause of increases in mercury concentrations in fish in newly flooded reservoirs is increased rates of supply of methyl mercury to the food chain (Bodaly et al. 1997; Lucotte et al. 1999). Organic carbon stored on upland and wetland sites prior to flooding in soils and vegetation are degraded by microbes and increased microbial activity results in elevated rates of mercury methylation. Large stores of methyl mercury build up in flooded soils and peat after flooding and some probably diffuses into the overlying water column, some probably enters the food chain via benthic invertebrates, and some becomes available due to the physical disruption of flooded soils by wave erosion. However, it would appear that much of the methyl mercury that is produced does not enter the water column or food chain but rather is demethylated in situ (St. Louis et al. 2004; Lucotte et al. 1999).

In boreal reservoirs, the pulse of methyl mercury supplied to the food chain is probably relatively brief. Elevated concentrations of MeHg in water and zooplankton have not been observed more than 8 - 10 years post-flooding (Bodaly et al. 1997). This short-lived pulse of MeHg production in reservoirs is delayed as it moves up food chains, due in part to the presence of long-lived fish populations in boreal reservoirs, resulting in elevated concentrations in fish for much longer periods (Fig. x). Water level drawdown may be expected to have an effect on the period of elevated MeHg in the food chains of reservoirs but the direction of the effect and the causes for it are unclear (Lucotte et al. 1999).

Mitigative Measures

Extensive mitigation works for fishes have been undertaken in Canadian reservoirs and especially in the more recent ones. Mitigative measures are aimed at improving fish habitat (creation of spawning areas, wood clearing, weirs, fish shelters, etc), providing fish passage (upstream and downstream) and managing fish resources (fish stocking, predator control, etc.). Although mitigative efforts have increased over time at hydroelectric projects, quantitative documentation, from initial design to implementation and monitoring effectiveness, is often lacking (Hill 1995).

A review of biological mitigative measures for Canadian hydro facilities was made some 20 years ago by the Canadian Electrical Association (Hill 1984), forming a useful reference document, but this exercise was not repeated. It was then concluded that more monitoring and detailed record keeping appeared to be warranted in many cases. A report was also produced by DFO to examine fish habitat mitigation techniques for their applicability to hydrotechnical projects in Canada (McPhail et al 1992). Fish protection system designs at hydroelectric generating stations are also provided in Ellis et al (1982) and guidelines for evaluating and recommending mitigation techniques that can be used at water power developments are given in B.A.R Environmental (1990, 1991). In Quebec, evaluation of mitigative measures for hydroelectric projects is discussed in Verdon (1998) and St-Georges (1991).

Bank and shoreline protection works have been constructed locally, but the cost of extending these works to large areas are prohibitive. In large reservoirs, the widespread nature of changes renders most remedial measures impractical and uneconomic (Bodaly et al 1984a). A comparison of the advantages and disadvantages of clearing terrestrial vegetation prior to flooding of reservoirs is discussed in Ploskey (1985).

The major requirement for knowledge related to mercury in reservoirs is the need for practical mitigation tools to decrease the severity and/or duration of elevated concentrations in the food chain. A desirable, but not essential, feature of a practical mitigation measure for reservoirs is that it would also be applicable to natural lakes. Many possibilities for mitigation of elevated mercury concentrations in the food chains of northern reservoirs have been suggested. These include:

1. site preparation techniques such as removal or burning of vegetation. Vegetation removal or burning would reduce the amount of organic carbon flooded and thereby reduce the production of methyl mercury after flooding;
2. the addition of selenium to reservoirs after flooding. Selenium in freshwater systems has been shown to reduce rates of mercury methylation and bioaccumulation of methylmercury in the food chain (Jin et al. 1997; Paulsson and Lundbergh 1991);
3. intensively fishing reservoirs after flooding. Intensive fishing removes methylmercury from freshwater systems and also tends to increase growth rates in fish populations, which reduces concentrations in individual fish by growth dilution (Göthberg 1983; Verta 1990).

However, solutions that are cost-effective and practical have so far been elusive.

Burning terrestrial plants and soil before flooding may mitigate MeHg contamination in reservoirs. Fires cause Hg and C to be lost to the atmosphere and may thereby decrease rates of mercury methylation in new reservoirs.

Burning before flooding may be beneficial locally, but it would redistribute Hg into other ecosystems. Controlled forest fires may be expensive and difficult to manage. An experiment that tested the effects of burning before flooding on MeHg concentrations in water, sediment, periphyton, zooplankton and benthic invertebrates found that burning reduced MeHg in water but not in biota, because of the modification of biomagnification by dissolved organic carbon (Mailman 2003).

Adding selenium to aquatic ecosystems may lower Hg concentrations in fish by several mechanisms, including decreasing the trophic transfer of MeHg (Turner and Swick 1983), and lowering rates of mercury methylation (Jin et al. 1997). Se additions to lakes have been shown to be effective in reducing Hg in fish in lakes in Sweden (Paulsen and Lundbergh 1991). Se is an essential element at low concentrations but can be toxic at elevated concentrations. The "window" between concentrations that are effective at modifying Hg cycling and concentrations that are toxic needs to be determined.

Intensively fishing a lake or reservoir of any age may potentially lower MeHg concentrations in fish. This has been demonstrated in a number of studies (Verta 1990; Göthberg 1983) and is currently under investigation in Quebec (J. Doire and M. Lucotte, University of Quebec at Montreal, unpublished data). Intensive fishing may lower MeHg concentrations in fish by several different mechanisms including (1) removal of MeHg from the system, (2) increase in fish growth rates, and (3) alteration of the food web structure. Increase in the growth rates of fishes by decreasing population densities and intra-specific competition seems to be the dominant mechanism. Intensive fishing seems less applicable to reservoirs because increased fish growth rates occur naturally in reservoirs, as a result of increasing nutrient content, and does not prevent increased Hg levels in fish because methylation of mercury in the sediment would continue in new reservoirs, intensive fishing may have to be repeated periodically until the rate of methylation subsides. Also, the biomass of fish that may have to be removed from large reservoirs would be substantial. In many cases, fishing with nets would require removal of trees at selected fishing sites before flooding.

Other potential mitigation methods for Hg contamination in reservoirs include additions of clay and sediment that would tend to reduce mercury methylaton in flooded soils, addition of lime to the catchment area or aquatic ecosystem that would tend to increase pH levels and thereby reduce rates of methylation and bioaccumulation, and the addition of genetically engineered bacteria to demethylate MeHg. More research is needed and this is the major knowledge gap related to mercury problems in hydroelectric reservoirs.

Reservoir Operation

Once the dam is operational, a myriad of factors are considered when managing reservoir water. Management objectives of storage reservoirs include to retain incoming water and to moderate release of water downstream to control flows for power generation and flood control. Reservoir water level magnitude, timing, duration and frequency are typically different from those of unmanaged lakes. These differences can include a delay or reduction in spring filling, maintenance of stable levels throughout the summer, and extensive drawdown in winter due to high electricity demand and spring flood prevention. Reservoirs created within an original river channel often occur immediately upstream of the generating station (head ponds), and may be operated with more frequent fluctuations than one created from an existing lake; storage reservoirs are often located upstream in the watershed and are generally operated with more extreme fluctuations in terms of magnitude than a head pond. However, generalizations regarding operations are difficult to outline given the variety of site-specific factors considered for operations of individual reservoirs.

A number of literature reviews pertaining to hydroelectric development and operations in Canada are available, including: Stokes et al. (1999), House (2001), and MNR (2002). Outside of Canada, the World Commission on Dams compiled a thematic review of dams, ecosystem functions, and environmental restoration (e.g. Bergkamp et al. 2000, King et al. 2000, McAllister et al. 2000), and FAO Fisheries Department produced a technical paper on Dams Fish and Fisheries: opportunities, challenges, and conflict resolution (Marmula 2001).

Habitat Modification

Changes in the magnitude and timing of water level fluctuation can adversely alter water quality, substrate type and littoral and riparian habitat. Higher water levels may result in reduced littoral productivity by restricting light penetration to the lake bottom, particularly for steep slopes. Sediments subjected to drying and freezing were found to release over 70 times more phosphorus over controls, which could increase internal phosphorus loading to systems subjected to winter drawdown (Klotz and Linn 2001). Sediment subject to drawdown showed a decrease in moisture content and organic matter, an increase in density and a decline in phosphorus within the sediment after drawdown (James et al. 2001). A phosphorus budget model created for reservoirs in Labrador underestimated phosphorus concentrations until a leach loading component was built into the model to account for the rate of loss from sediment and vegetation (Ostrofsky 1978). No change in water chemistry was detected over a three year experimental drawdown in the Experimental Lakes Area of Ontario (Jansen 2000). Regulated lakes or reservoirs trap sediments, which over the long term limit the useful life of a reservoir by reducing storage capacity and in some cases has resulted in abandonment (Cairns and Palmer 1993), but this issue is of less importance in Canadian Shield reservoirs. Reservoirs can also trap nutrients along with sediment, which has resulted in the oligotrophication of some large, deep reservoirs in B.C., and the subsequent reduction in fish populations (Ashley et al. 1997).

Research into the effect of reservoir operations on riparian and littoral zone flora is relatively recent and thorough. Reservoir management can result in bi-directional level changes of many meters in magnitude, increasing both within- and among-year variability, creating an extensive transition ecotone that vacillates between acting as a riparian or littoral zone, preventing the establishment of sensitive rare species (Hill et al. 1998). Permanent flooding results in tree mortality, but the effect of an elevated water table are less known

(Kilmas 1982). Wetland tree communities, particularly larger trees, were shown to be sensitive to flooding, which caused a shift towards a shrub community and more tolerant tree species that could reproduce clonally (Ernst and Brooks 2003). Increased water levels have been implicated in reduced growth, increases in tree stress and decline (measured by crown dieback, thinning, rot, discoloration etc), and mortality at a number of locations in North American and elsewhere, subject to impoundment and regulation (e.g. Chong and Ladson 2003; Conner et al. 1993; Connor and Day 1992).

Altering the duration and range in regulated lake water level fluctuations has been shown to increase shoreline erosion due to a transfer of wave energy shoreward (Lorang et al. 1993). Shoreline erosion can eliminate existing vegetation and prevent the establishment of submergent and emergent vegetation, and can alter morphometry further decreasing habitat complexity (Poddunby and Galat 1995). The loss of vegetation and deposition of sediments through erosion processes can result in poor habitat quality for fish (Meals and Miranda 1991). Over the long-term, shorelines of storage reservoirs were found to have lower densities, lower species richness and different flora relative to adjacent unregulated rivers; run-of-the-river systems had lower species richness, but similar density and community composition characteristics relative to free flowing systems (Nilsson et al. 1997).

In unregulated lakes, species richness patterns of both common and rare shoreline plants were best predicted by the amplitude of normal water-level fluctuations (Hill and Keddy 1992). Variability in water-levels prevents the establishment of woody plants and dominance of large species, which can exclude smaller species, to the benefit of riparian biodiversity (Hill et al 1998). Maintaining artificially stable water levels can eradicate wetlands to the benefit of riparian vegetation communities (Nilsson and Berggren 2000). A comparison of macrophytes among lakes under varying degrees of regulation showed that large scale fluctuations resulted in dominance by rosette and matt forming species; reduced fluctuations resulted in dominance of erect macrophytes that extended through the water column; and the unregulated system supported structurally diverse plant communities (Wilcox and Meeker 1991).

Reservoir developments now more often use digital elevation to predict the area to be flooded, and harvest the standing forest prior to flooding (Tundisi et al. 1998). Nonetheless, reservoirs still exist with standing forests, can which contribute above-average woody habitat to connected systems. In addition, reservoirs trap wood that is transported from upstream in the watershed (Moulin and Piegay 2004). Periodically, wood that accumulates in reservoirs needs to be mechanically extracted to avoid damage to dams, turbines, or reduce navigation hazard. Woody habitat in lacustrine systems is believed to provide shelter from predation, serve as spawning substrate, and provide additional surface area for primary and secondary production. Yet, although the importance of woody material in diversifying habitat in lotic systems has been demonstrated, empirical evidence regarding the contribution of woody habitat to whole system production in lakes is lacking.

Biological productivity

Short reservoir retention times (~ four weeks) limit autotrophic production; retention times longer than a year are associated with strong stratification (Søballe and Kimmel, 1987). Zooplankton biomass was significantly correlated with water retention time in a Newfoundland reservoir, but not with temperature, nutrients or primary productivity (Campbell et al. 1998).

Rapid water level decrease can be more detrimental to aquatic invertebrates than fish since they are less able to adjust to receding water levels (Sharp and Keddy 1993). Drawdown during winter has a number of implications, including the freezing of sediment in the drawdown zone and reducing macroinvertebrate biomass and diversity in those zones (Palomäki and Koskenniemi 1993). Biomass of invertebrates was shown to be greater in a natural lake by a factor of 2-3 relative to a regulated system, and taxa composition was altered to be predominantly chironomids and mites, the latter of which did not form part of the resident whitefish diet (Tikkanen et al. 1988). Tikkanen et al. (1988) found a greater proportion of plankton in the whitefish diet in the regulated system and concluded from stomach content and fullness analysis that there was a lack of suitable food for whitefish in the regulated lake; perch stomachs were also significantly emptier until they became piscivorous, a transition which occurred when perch were smaller in the regulated system.

Lake 226 in the Experimental Lakes Area, Ontario, was the site of an experiment to determine the effects of winter water level reductions on fish habitat, fish populations (whitefish focus) and productivity (Jansen 2000). Over three consecutive winters water levels were reduced by 2-3 m and allowed to partially recover each summer, designed to simulate operations in boreal hydroelectric reservoirs. All levels of the ecosystem were monitored from water chemistry through to food web effects. Littoral zone macrophytes, macroinvertebrates, and periphyton were all disrupted by the experimental drawdown, but zooplankton and phytoplankton were not affected (Jansen 2000).

Water levels on the highly studied Rainy River system, Ontario and Minnesota, are regulated by several dams which have the effect of reducing magnitude of fluctuations for Rainy Lake and increasing the mean annual fluctuation of Namakan Reservoir, but overall reducing variability relative to unregulated Lac La Croix, which serves as a control lake within the same watershed (Cohen and Radomski 1993). Kraft (1988) found that invertebrate species richness was greatest at 1 m depth in Rainy Lake, but that maximum diversity wasn't reached until 3 m in the Namakan Reservoir. While Kraft attributed these differences to large winter drawdowns in Namakan, Wilcox and Meeker (1992) demonstrated the differences could be indirectly due to different macrophyte composition in areas subject to varying regulated regimes. The morphometry of the reservoir will influence the extent of exposed area, with a relatively smaller impact zone in steep-sided systems.

Changes in fish communities

A large proportion of reservoir fishery research was conducted in areas outside of Canada throughout the 1970s and 1980s, due to the increasing proportion of standing waters that are classified as reservoirs, and the growing importance of reservoirs in sport and commercial fisheries (Fernando and Holčík 1991, Miranda 2001). The development of successful fisheries in reservoirs is subject to constraints not present in natural lakes; reservoirs are artificial systems subject to flow through and level fluctuations dictated by operational objectives, although fish and aquatic habitat are an increasingly important priority in decision making. Currently in Canada a wide variety of factors are considered when negotiating operating regimes, including environmental issues, competing water uses, technological development and market restructuring (CEA 2001).

In their review of world reservoir fisheries, Fernando and Holčík (1991) demonstrate that only the broadest generalists in regards to food and reproductive requirements are able to inhabit the new lacustrine environment, which can result in a depauperate fauna relative to rivers. While generalists quickly occupy reservoir littoral zones, the pelagic zone in reservoirs remains unoccupied, particularly in large and deep reservoirs, unless a species preadapted to lacustrine environments exists in the watershed. An analysis of the Bridge River and Carpenter reservoir (B.C.) food webs found that fish stable isotope signatures were more similar to invertebrate drift from the middle Bridge River and reservoir chironomids, and were not similar to zooplankton or tributary drift (Leslie 2003). However, since it was not possible to distinguish between these two prey resources, clear recommendations regarding the optimal management strategy to maximize fish production could not be made. Establishing successful pelagic fish populations less dependent on littoral zone habitats could be important for maintaining fishery yields in reservoirs with large water level fluctuations.

Fisheries managers have introduced species into reservoirs with the objective of enhancing the fishery, and as a result, many reservoirs contain both native and introduced species in an artificial habitat subject to regulation (e.g. Tikkanen et al. 1988; Gelwick and Matthews 1990; Ney et al. 1990). Success of efforts has been varied, and management of introduced species can be an ongoing process with unexpected biotic interactions necessitating changes to stocking levels or by conducting additional introductions in an attempt to achieve some stability in the fishery (Johnson and Goettl 1999). Fish stocking can disrupt fish communities, reduce genetic diversity and extirpate native species (Schramm and Piper 1995). Gelwick and Matthews (1990) argue that reservoir species assemblages and associations are not similar to lakes due to the relatively short evolutionary timeframe the assemblage has inhabited the environment, coupled with the influence of fluctuating water levels deterring formation of well-structured species associations. Changes in interspecific interactions among piscivores were found to correspond with water level regulations (Cohen and Radomski 1993).

In Rainy Lake and Namakan Reservoir, year class strength of northern pike and yellow perch was greater in years with higher lake levels in spring, which provided access to flooded vegetation spawning habitat during critical water temperatures (Kallemeyn 1987). Wilcox and Meeker (1992) hypothesized that delaying water-level peaks limits access to nearshore and shoreline vegetation during spawning season, and limited structural diversity reduces protective cover in shallower feeding and nursery habitat of Namakan Lake; in Rainy Lake dominance of emergent macrophytes may limit feeding by piscivorous fish. As a result of extensive research demonstrating detrimental effects of the operations on this cascading system, and by using a hydrological simulation model to analyze and evaluate a variety of operations, in 2000 a new rule curve that more closely approximates natural variability was ordered by the International Joint Commission (Kimmett et al. 1999). In the U.S., recruitment success of bass and other species has been linked to high water during spring flooding in a number of reservoirs, and as a result a number of reservoirs are now managed for spring flooding based upon this empirical evidence (Sammons and Bettoli 2000).

Populations of fall spawning fishes can be negatively affected by winter drawdowns via affecting egg survival and incubation (Gaboury and Patalas 1984, Ploskey 1985). A drawdown of extended duration due to dam failure in South Carolina resulted in the temporary loss of the littoral zone and its associated vegetation, and a reduction in habitat size and quality. Fish species richness and abundance declined significantly during the first year with the loss of small, shelter-seeking species, and the loss of juveniles of larger species (Paller 1997). While Paller (1997) indicates that short winter drawdowns could have a similar effect, recovery was rapid after refilling due to recolonization by fish surviving in refugia and highly successful reproduction, indicating a resiliency to prolonged stress due to drawdown – which may or may not be characteristic of reservoirs in colder climates such as Canada.

In the Lake 226 experiment a 2 m drawdown resulted in a habitat loss of 14% by area and 24% by volume; a 3 m drawdown 31% area and 45% volume habitat loss. Spawning habitat was exposed each year causing complete recruitment failures, survival was reduced due to lower oxygen, and there was an 80% cumulative reduction in whitefish abundance over the three years of drawdown (Jansen 2000). Once drawdowns terminated, whitefish recovery was not as rapid as expected with growth and recruitment showing weak signs of recovery, which was attributed to a disruption in food supply via loss of littoral zone and reduced littoral zone invertebrate abundance.

Research into the seasonal habitat use of fishes in reservoirs, particularly in the US, is relatively common (e.g. pike, Cook and Bergersen 1988, Jepsen et al. 2001; burbot, Bergersen et al. 1993; palmetto bass, Jones and Rogers 1998; fish communities, Poddubny and Galat 1995). If few high quality littoral habitats are available, fish may travel longer distances between spawning, feeding, and wintering habitat, increasing energetic costs for swimming activity, thereby reducing energy available for growth and reproduction. Bégout Anras et al. (1999) assessed spawning habitat use of Lake Whitefish during the drawdown of Lake 226 and found high fidelity to specific substrate types and slope, with shallower sites selected when water levels were higher during spawning.

Drawdown resulted in the desiccation of up to 70% of spawning sites, with remaining sites partially exposed to cold and ice conditions during initial stages of incubation.

Annual fish yields in reservoirs are highly variable in different types of reservoirs and in different parts of the world, but on average are considered low, particularly in northern environments (Fernando and Holčík1991). However, Jenkins (1982) a found that fish yields in U.S. reservoirs was greater than in north temperate lakes. Randall et al. (1995) demonstrated that rivers were more productive than lakes, and hypothesized that greater reservoir productivity resulted from reservoir inflow and turnover rates being more similar to rivers than lakes.

Modelling has been used extensively to aid reservoir management and to provide a means of risk analysis under different scenarios. Kallemeyn and Cole (1990) describe an assessment method for alternative rule curves using ranking factors developed for resources in the Rainy Lake watershed. Results ranking the effect of alternative rule curves were entered into a matrix that allowed comparisons between alternatives, and the rule curve that optimized power production while improving ecological conditions was adopted in the system. The benefits of the altered operations are still being assessed (Meeker and Harris 2003). A similar approach was used in B.C. water use planning where the interests of all stakeholders were accounted, and performance measures were generated for various management alternatives, attempting to use trade-offs to optimize the management strategies implemented for all stakeholders (Macfarlane, DFO, personal communication). While some model components were transferable across watersheds, some components and performance measures needed to be developed on a site-specific basis. A variety of models have been published to predict fish (Bennett et al. 1985, Frisk et al. 1988) and ecosystem response to various management scenarios (e.g. Ismaiylov et al. 1993, Salençon and Thébault 1996, Menshutkin and Klekowski 2001, Saito et al. 2001)

Mercury in Fish

It is clear that newly flooded reservoirs tend to export methyl mercury to downstream systems and thereby cause increases in mercury in fish downstream of the reservoirs itself. This can happen because fish from reservoirs suffer mortality or stunning when entrained in turbines; these fish can become prey for predatory fish resident below the turbines (Brouard et al. 1994). It can also happen because reservoirs export methyl mercury in water, on particles, and in drifting zooplankton and invertebrates (Johnston et al. 1991, Schetagne et al. 2000). The downstream effect of reservoirs can be felt as much as 275 km from the reservoir (Schetagne and Verdon 1999).

There are a number of instances of reservoirs in which there would appear to be a link between annual water level fluctuations and Hg concentrations in fish, including reservoirs in Wisconsin and British Columbia. However this link is not well established and data interpretation has been complicated by the presence of confounding factors. Research is needed in this area and is the subject of a recent request for proposals by Minnesota Power, Duluth.

Mitigative measures

One adaptive management experiment conducted on a regulated lake that was deemed a success is the Kootenay Lake fertilization experiment in B.C. (Ashley et al. 1997). The adaptive management process was rigorous in this study with the development of a quantitative productivity model used to analyze management alternatives (Walters et al. 1991), and intensive monitoring at all major components of the ecosystem (Ashley et al. 1997). Quantifying population responses allowed for the adjustment of fertilization levels to enhance fisheries while avoiding excessive nutrient loading (Ken Ashley, personal communication). Other fertilization programs have since been implemented in the Arrow Reservoir, Alouette Reservoir and Jones Lake Reservoir in B.C., but in the case of the Alouette Reservoir, fertilization was conducted as mitigation for lost fish productivity via entrainment at the Stave generating facility (Steve Macfarlane, DFO, personal communication).

Mitigation of shoreline erosion is possible by altering the timing and duration of drawdown with the goal of reducing the amount of annual wave energy that reaches the foreshore environment (Lorang et al. 1993, Miranda 2001). Alternatively shoreline stabilization techniques such as armouring with riprap or planting vegetation have been used to control erosion and sedimentation in reservoirs.

One mitigation measure which has been used with some success is to enhance structural habitat complexity in the nearshore area of reservoirs (Hunt and Annett 2002). While some studies have shown that artificial or introduced habitat has been used by fish species and that sometimes that use was greater than on natural spawning areas (Frankiewicz et al. 2001), no published examples of long-term improvements in whole-system fish response resulting from habitat addition were found. The expense and effort of adding structures results in the alteration of a small proportion of the shoreline and ongoing maintenance can be required to maintain their benefit. Alternatively, some authors have suggested leaving areas of standing timber for flooding to provide more fish cover than post impoundment additions (Ney et al. 1990). The creation of spawning shoals below the reservoir drawdown limit is also suggested as an appropriate mitigation for winter drawdown (CEA 2001).

Access to tributaries can be very important for some reservoir species therefore impediments to access should be removed, including sand bars that may block access to tributary mouths (Poddubny and Galat 1995). Reservoir tributaries can also be subject to backwater effects from the reservoir; addition of suitable spawning substrate upstream of the backwater effects is a suggested mitigation (CEA 2001). Another option used to enhance access to spawning habitat was to construct wave-control dikes that control water levels providing access to spawning and rearing habitat along shorelines (Avakian and Poddubnyi 1995). The success of these areas depends on location, extent of fluctuations, full knowledge of local conditions, and life histories of target fish populations. Aquaculture facilities placed in isolated littoral sites that are not used by other species can also increase reservoir fish production (Avakian and Poddubnyi 1995).

Whether the reservoir was formed from a river channel or an existing lake can determine its response to mitigative measures, with potentially greater success achieved from former lake systems. Flooded systems that contain riverine fish fauna preadapted to lacustrine conditions, or with introduced lacustrine species, should produce a higher fish yield than those without (Fernando and Holčík 1991). Stocking of juveniles can supplement a native fish population if reproductive success is limited (Martinez and Wiltzius 1995), and stocking to restore threatened or endangered species has had some success (Miranda 2001). Of course, careful scientific consideration of all implications must occur before implementing any species introduction as a mitigative measure to increase fish yield, and this option is often considered an option of last resort by resource managers.

Currently, the most often cited mitigation technique is to use the main variable altered in reservoir operations – i.e. adjusting the magnitude, timing and duration of water level fluctuations. Numerous authors have suggested that water levels be regulated to approximate the amplitude and timing of natural systems. Ecologically based operations in Finnish reservoirs now include a well defined spring flood target and higher winter water levels (Hellsten et al. 1996). Operational constraints considered in Canada for fish and fish habitat can include target reservoir levels, drawdown restrictions, early spring filling and balancing flow in cascading systems among facilities (CEA 2001). However, in order to establish a rule curve incorporating natural variability in water levels, information on natural variability and how that variability can be quantified and applied to ecosystem management is needed.

The regionalization approach, predicting flow curves for ungauged rivers and levels for lakes (e.g. Omernik et al. 1991, Cassie and El-Jabi 1995, Harding and Winterbourn 1997, Quinlan et al. 2003) has been used to better understand reference conditions and make scientifically based management decisions for water resources. For reservoir management, Ontario is adopting an ecoregion approach (Harding and Winterbourne 1997, Johnson 1999, Gronskaya 2000) to partition the landscape based on broad patterns in climate, geology, vegetation, soils and land use. Lakes classified within an ecoregion show strong coherence in physical variables such as water level and temperature, and can provide a basis for extrapolation of general trends across a region. Analyses of data from gauged lakes in Ontario demonstrated that general patterns of water level fluctuation were similar across ecoregions and can provide a basis for reservoir management (Krezek et al. 2004). Implementing the natural flow regime paradigm in Ontario will recognize existing operational constraints and should be conducted in an incremental manner coupled with monitoring to evaluate the effectiveness of change (MNR 2002).

Ontario's waterpower facilities are required to prepare a Water Management Plan (WMPs) that will set enforceable operational requirements for the management of water flows and levels to ensure the environmental, social, and economic well being of the people of Ontario through the sustainable development and management of waterpower. Fisheries and Oceans Canada is also involved in this process to ensure that WMPs are in compliance with the Fisheries Act, and OMNR and utilities are asking that authorizations be issued if all effects cannot be mitigated.

Likewise, all hydroelectric facilities in British Columbia are required to have Water Use Plans (WUP) which incorporate considerations and trade-offs among multi-stakeholders, multiple uses and ecological functions. Limited resources are available for implementing mitigation measures in WUPs so the objective is to find the most efficient and equitable way to use available resources to provide protection and enhance fisheries and aquatic resources if possible (Higgins 2001). Water use plans are to be prepared for all watersheds influenced by B.C. Hydro's operations, and will define detailed operating parameters to be used in daily decision making. Adaptive management is an integral part of reducing uncertainty in WUP decisions.

Common to both methods is the use of the ecosystem based approach to address planning issues associated with the ecological integrity of the regulated environment. Natural patterns of flows and levels are important for maintaining ecological function and can be used to identify comprehensive ecosystem-based flow and level objectives. The ecosystem approach considers the system in a holistic manner – no longer managing for single species but to address all components relating to the structure and function of an ecosystem. Since different species have different requirements for optimal life history strategies, managing for an individual species can result in negative impacts on other species or other trophic levels. Dam operations have the potential to disrupt complex trophic linkages which can have indirect effects on target species (Wootton et al. 1996). Therefore using an ecosystem based approach to management and monitoring is important to maintain a dynamic, well functioning ecosystem. While this approach may be temporarily detrimental to a target species of interest, natural variability of a system contributes to its resilience and long-term sustainability. Resource managers have recognized the need for water management at an ecosystem level, recognizing that managing for individual species and activities is counterproductive since ecosystem level processes must be maintained to sustain the long-term provision of water for human use, as well as to allow the system to respond to changing environmental conditions (Borre et al. 2001, Randhir et al. 2001; Baron et al. 2002).

Mitigation of the effects of reservoir operations on elevated concentrations of mercury in fish and food chains downstream of reservoirs has received little thought or attention. Any action that would tend to reduce Hg in food chains in northern reservoirs will also tend to reduce Hg in receiving waters downstream from reservoirs. Elevated Hg in predators found immediately downstream of generating stations due to the consumption of fish stunned or killed in turbines would be reduced by decreasing fish entrainment in turbines.

KNOWLEDGE GAPS AND RESEARCH RECOMMENDATIONS

Habitat Modification

Although few studies are related to thermal regime in reservoirs, this issue is not critical for fish composition and productivity above dams. Even though such impacts are not well documented, thermal differences between pre and post-flooding conditions are not large enough to cause notable differences and other habitat components are probably much more influential on fish communities. On the other hand, thermal regime below dams would often alter fish composition and these effects are pretty well documented.

The effects of reservoirs that are optimally managed for power production and flood control on erosion, riparian zones, macrophytes, and benthic invertebrates, have been demonstrated for a number of systems and some generalizations can be made and applied to Canadian systems. Effects of operations on primary productivity, temperature, and oxygen are varied and dependent on morphometry, climate, type of reservoir and operating regime. Water quality and nutrient dynamics are aspects that are well documented and good models exist to predict water quality characteristics following impoundments. Therefore, we would not recommend high research priority for these issues. Response of biological productivity to impoundment, at least at the lower level of the food chain, is generally well understood, since such studies were generally carried out along with water quality monitoring. Primary production and zooplankton response have been described on several occasions, and this area does not warrant high priority.

Benthic communities and the colonization process have been studied in several reservoirs and are generally well understood. However, the role of submerged trees and impact of drawdown on benthos should be devoted more attention. Macrophytes are generally lacking in reservoirs, especially where drawdown is important. On the other hand submerged trees and branches are normally an important component of the reservoir, but their role in fish habitat is not well understood. They may act as support for benthic organisms and shelter for fish, but how fish use them and how it influences fish production has not been studied, partly because of the difficulties to efficiently sample these habitats.

Changes in Fish Communities

Fish adaptation to reservoirs is species specific. Species that are well adapted and those which are less resilient are well known. Numerous empirical and a few experimental studies on the effects of reservoir operations on fish populations have been conducted, and evidence is relatively strong demonstrating effects on behaviour, growth, spawning success and recruitment. Unfortunately, each watershed is physically, ecologically and operationally unique, so extrapolating from existing knowledge to make site-specific management decisions in the absence of a thorough examination of site specific factors would be risky.

There is a lot of uncertainty related to the estimation of fish productivity and yield in reservoirs (Power 1992). This is critical in the context of the Canadian Policy for the Management of Fish Habitat (1986), where proponents of hydro projects must quantify gain and losses in the capacity of production resulting from habitat alteration and reservoir creation. Methods to evaluate fish yield based on physico-chemical characteristics of Canadian reservoirs, such as the morphoedaphic index for north-temperate lakes or empirical models developed for U.S. reservoirs (Jenkins 1967), are lacking. Such tools should be examined.

Cumulative impacts result from direct and indirect effects of an activity and can occur over a large geographic area, over a long time frame, and in an additive, synergistic, or threshold manner. Cumulative impacts should be assessed, but currently no one model, tool, or management strategy has been promoted as a standard for cumulative effects assessment. Watershed Management or Use Plan will aid in cumulative effects assessment since they are conducted at a more suitable scale than single system management strategies.

Uncertainty is a significant variable that has historically not been accounted for in most resource management decisions. Uncertainty comes in a number of forms and can arise from a lack of baseline data, uncontrollable natural variability in ecological processes, uncertain knowledge regarding the relationship between fish and fish habitat or other ecological processes, resulting uncertainty in modelling parameters to predict ecological impact, the effect of external or confounding factors, and the selection of appropriate measurement variables and monitoring design to impart statistical reliability in results (Higgins 2001). The need to account for uncertainty is becoming increasingly apparent due to the potential ecological and economic consequences of using simpler methods that ignore uncertainty. Methods on how to incorporate risk and uncertainty into decision making have been expanding in recent years and involve quantitatively incorporating uncertainty into a management decision framework. Adaptive management can be one tool that can account for uncertainty in decision making by testing deliberate planned comparisons of alternative management options.

Mercury

Prediction of the spatial and temporal extent of the elevation of Hg in fish in new reservoirs is required to be able to assess the impacts of new developments and to minimize impacts. Accurate prediction will allow the relative impacts of alternative sites and project configurations to be compared. Prediction of Hg in food chains and fish due to the flooding of terrestrial areas has been possible for some years by using simple models that relate amount of terrain flooded to increases in the supply of MeHg in flooded systems (Johnston et al 1991; Messier et al. 1985). Recent research at the Experimental Lakes Area, supported by Manitoba Hydro, Hydro-Quebec and the former Ontario Hydro, has concentrated on studies that have experimentally flooded areas of homogeneous vegetation to establish the relationship between the intensity and duration of MeHg production and terrain type (e.g. Kelly et al. 1997; Bodaly et al. accepted). Also, dynamic, mechanistic models based on the cycling of mercury through various ecosystem compartments (flooded soils and vegetation, water, the food chain, fish) are now becoming available for use as predictive and planning tools.

The Manitoba Hydro Mercury Model for Reservoirs is currently being updated and calibrated based on the results of sampling of experimental and actual boreal reservoirs. A mechanistic model, based on a bioenergetic model (University of Wisconsin 1997) and a bioaccumulation model (Rodgers 1994) is being developed by the University of Sherbrooke (Ruiz et al 2001). Thus, prediction based on realistic dynamic models is now possible and this is probably not a major knowledge gap at present.

Mitigative Measures

Alternative shoreline stabilization techniques (riprap, gabions, breakwalls, and vegetation planting) have been used to control erosion and sedimentation in reservoirs, but published results on the effectiveness of these efforts were not found. Little evidence could be found regarding the success of structural habitat modifications, including the addition of spawning habitat below the reservoir drawdown limit, of the addition of spawning habitat in tributaries above the level of inundation. Thus, the main gap related to mitigative measures in reservoirs is related to measure of their effectiveness. Hill (1984) recommended an update of the report on biological measures (e.g. every 5 to 10 years) to maintain a reference handbook for utilities that provide state-of-the art guidance on alternatives for mitigation and an evaluation of their effectiveness. This recommendation is still relevant and should be put forward.

Assessment of structural habitat additions or alterations is a relatively simple research program if the objective is to quantify the use of the created habitat by target fish species on a site specific basis. However, these types of assessments have been extensively carried out in natural lakes and oceans, yet little to no evidence exists regarding the effectiveness at a population level (Smokorowski et al. 1998). Incorporating an examination of the use of artificial habitat structures could form part of an integrated monitoring program.

There are numerous demonstrated links between water levels and flora and fauna that support mitigating effects via altering the hydrology of the system towards a more natural regime, or if that is not operationally feasible, to adjust water level rule curves towards more ecologically friendly options. Most of the published studies are based on empirical correlations, which when considered together provide strong support for this paradigm. A number of Canadian reservoirs are now incorporating environmental considerations in operations including increasing productive potential of littoral zones, elevated water in spring for pike and bass spawning, and control of winter drawdowns for protection of fall spawning areas (CEA 2001). Yet there is a lack of published results from experimental research, adaptive management, or effectiveness monitoring efforts to clarify if implemented mitigative measures achieve the desired results. Because year class strength of fish vary naturally depending on environmental conditions, the annual manipulation of water levels for optimal fisheries may not be necessary or productive (Miranda 2001). Testing alternatives in management regimes on regulated systems through carefully planned monitoring programs and experiments could allow for optimal tradeoffs between ecology and energy production.

GENERAL RECOMMENDATIONS AND ONGOING RESEARCH

Much information may already be available from effectiveness monitoring programs across Canada. Given that some Canadian reservoirs are incorporating environmental considerations in operations, it is highly probable that a monitoring program was included in the plan. Many of these results will be available only in consultants' reports or in data files at hydroelectric companies or government agencies. Due to the high costs of research and monitoring, it is also highly probable that individually the programs may not be as scientifically rigorous as desired, but cumulatively the results could be informative. A data mining and reporting exercise should be conducted seeking input from unpublished sources across Canada, and optimizing the value of monitoring efforts.

Whether mandated or voluntary, changes in operations directed to the benefit of the ecosystem can result in less than optimal operation for power production or other water uses. It is therefore important to ensure that mitigation efforts achieve the expected and desired outcomes and are ground in science. While some level of monitoring is essential, in select cases where the availability of historical data and other factors warrant, it would cost effective and highly valuable to conduct the changes in an adaptive management framework with a collaborative, well designed, multidisciplinary research program. Research should adopt an ecosystem approach and use a variety of techniques to measure the physical and chemical environments, plus multiple trophic levels, valued ecosystem components, and food web dynamics. This approach can be costly, but partnering, cost sharing, and maximizing collaboration can reduce cost, as can focusing effort on variables predicted to demonstrate a response, provide a mechanism for change in a valued ecosystem component (e.g. fish community or fish species of interest). In addition, adaptive management experiments can be much less costly than artificially creating reservoir conditions for the direct purpose of experimentation. Problems with successfully implementing adaptive management can include a lack of sufficient baseline data to understand the ecosystem in question to allow model development and prediction of outcomes, or to fully assess any benefit achieved.

In many cases techniques are still being developed to determine the most cost effective sampling designs, the best indicators, and how to analyze the results to provide concrete information and effective management recommendations based on science. A recent literature search for effectiveness monitoring programs was commissioned by Ontario MNR and they will be developing standard tools and designs to recommend for use in WMPs (Chong et al. 2003). Given that the current trend in Canada is to negotiate ecological considerations when relicensing or developing utilities, many opportunities will be available to use these operational changes in an experimental framework to address knowledge gaps. One key question in reservoir research is how far from natural variability in levels can operations deviate for a reservoir to remain viable, productive, and ecologically sound?

In Ontario, an assessment of the effectiveness of the more ecologically based, altered rule curve on the Rainy Lake-Namakan Reservoir system wetlands is currently underway (Meeker and Harris 2003). The Waterpower Science Strategy of OMNR has funded a number of research projects including: 1) the development of a standard sampling protocol to describe fish community structure in non-wadable streams; 2) the development of an Ontario Flow Assessment Technique (OFAT), 3) the development of an Ontario river/stream ecological classification technique (ORSECT), 4) assessing the natural variability in unregulated lake and regulated tributaries of the Batchawana River: a scientific basis for establishing realistic reference conditions to monitor the potential impacts of waterpower projects, 5) the development of littoral zone mapping and sampling methodologies in reservoir lakes, 6) the impacts of water management on fish in a large river, 7) the effects of altered flow regimes on the hyporheic zone, and 8) the provision of continuous daily flow data for waterpower facilities in Ontario. More information on each of these projects can be found at: http://www.trentu.ca/wscproject/wpscinfo/wpschome.htm.

The Bridge River WUP, B.C. includes an adaptive management experiment designed to assess minimum flow requirements in a riverine segment (Gregory et al. 2002). The Stave (B.C.) WUP, monitoring programs include assessment of littoral and pelagic production and limited assessments on wind and wave erosion. Riparian planting and assessment has occurred on the Upper Arrow Reservoir, Williston Reservoir and Stave Reservoir. Assessment work in Newfoundland includes using telemetry to study fish movement and habitat use within residual fluvial habitat, a newly created spawning/rearing channel and the existing reservoir at the Granite Canal hydro project.

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FIGURES

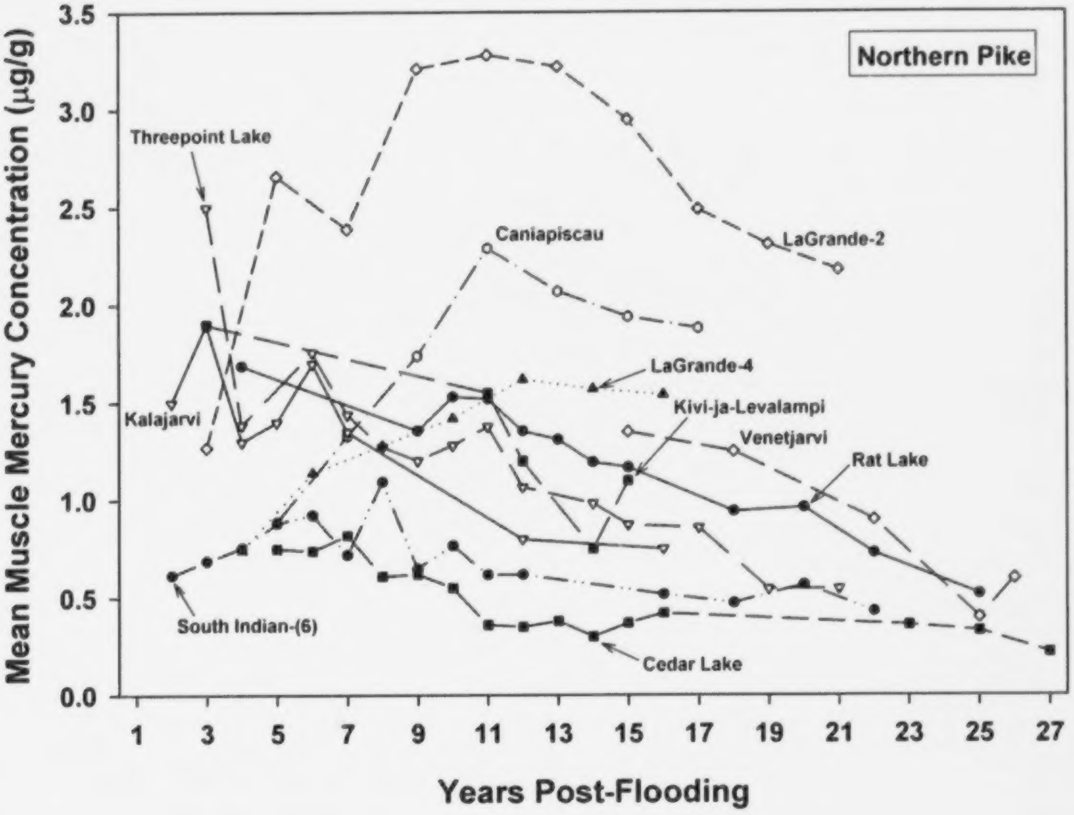

Fig. 1. Time course of concentrations of total mercury (µg/g w.w.) in the muscle of northern pike (Esox lucius) from boreal hydroelectric reservoirs located northern Manitoba and northern Quebec, Canada. Data from Quebec reservoirs from Schetagne and Verdon (1999) and R. Schetagne, Hydro-Quebec, Montreal, unpubl. data.

SUMMARY OF GROUP DISCUSSIONS FOLLOWING PRESENTATION

Following the presentation of this paper by Karen Smokorowski, the participants were encouraged to identify and discuss issues of relevance for Reservoir Science, particularly as they related to future research needs. A number of points and suggestions were identified.

- Determine whether mercury is a concern across the country; currently not studied in all areas of the country so existing models may not always apply.
- Issue exists with prediction and the ability to predict.
- Study mercury elevation in old reservoirs.
- Determine more on the reasons for the magnitude of upsurge in mercury.
- Gap exists in the generation of climate active gases from decomposition of organic material.
- Compare alternative of not making reservoirs.
- Evaluate the possible impact of climate change on reservoir ecology, flows and levels; study non-reservoir systems and research.
- Determine whether there are impacts from short term lowering for maintenance.
- Consider the difference between elevated levels in reservoirs versus nature.
- Document shift in habitat use; assess difference in species from lake to reservoir.
- Determine how to integrate effects of stranding, back water and entrainment, on survival.
- Consider tradeoff between harvesting forest before/after reservoir.
- Consider the impact of drawdown, including how quickly natural use returns, in summer and in winter.
- Assess suitability of mitigation measures to address HADD.
- Identify the critical contributing factors to erosion.

This input was quite helpful for the prioritization of future research in Reservoir Science.

Monitoring for Assessment and Learning?

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The provision for and importance of sound science advice is a key input to the formulation of federal regulatory policy and the management of environmental impacts. "Science advice" is guidance derived from scientific theories, data, findings, and conclusions provided to inform policy and regulatory decision making. Past approaches evaluating the ecological impacts of hydroelectric development and operation have not always resulted in the advancement of scientific understanding because of shortcomings in the follow-up monitoring and evaluation programs (Larkin 1984).

Monitoring is a fundamental element of water resource management. It is a practical method enabling three critical elements of water management to be undertaken: 1) the demonstration of compliance/accountability in terms of the implementation of specific management actions or regulatory requirements, 2) the determination of effectiveness of prescribed actions for delivery the expected non-power benefits (such as the protection or improvement of key species), and 3) the improvement of our scientific understanding.

Adaptive management has been widely advocated as the means to integrate research, monitoring and management, and to improve the scientific foundations for management (e.g., Clark 2002, Richer et al. 2003). Adaptive management (AM) differs from simple monitoring because the AM approach begins with the establishment of testable hypotheses about the relation between management actions and ecosystem responses. By designing the monitoring program to test hypotheses, uncertainty about management actions is decreased, scientific understanding improved, and more informed decisions in the future are possible. Further, the continuous interplay between scientists, decision makers and stakeholders implicit in AM may lead to improved institutional arrangements (Clark 2002). Adaptive management approaches are entrenched in policy for water resource management in many jurisdictions across North America, and is currently being applied in practice in some Canada provinces (British Columbia's Water Use Planning Process and Ontario's Water Management Initiative).

Two general approaches to adaptive management are most commonly considered: 1) passive and 2) active [or experimental] (Walters 1986). The passive approach is sometimes characterized as "modify and monitor" as it involves the evaluation of a single change to the ecosystem, such as an alteration of operating procedures. Active adaptive management refers to a deliberate set of management actions designed to learn about the ecosystem response. Although active adaptive management is by far the most powerful approach for reducing uncertainty about how an ecosystem will respond to change, it can be very expensive and time consuming. These limitations, as well as institutional and management constraints have generally limited its application (Walters and Green 1997).

KNOWLEDGE/POLICY/SCIENCE GAPS FOR MONITORING AND ASSESSMENT

This list of knowledge gaps is the result of a review of the literature, and our own experience with adaptive management and monitoring of water management projects in B.C. and the western U.S.

1. **Institutional/Policy Considerations**. Instituting adaptive management or requiring monitoring programs with feedback implies a different relationship between industry and government. Ideally, adaptive management should foster a culture of learning and cooperation.
2. **Risk assessment and the use of information**. The best monitoring programs will often yield ambiguous results. How will such results be used for decision making? What level of risk will the parties assume? Will the accounting for risk and uncertainty include economic and social factors as well as ecosystem components?
3. **Is monitoring the most efficient way to learn/make decisions**? Long-term monitoring may be less effective than focussed, process oriented research for elucidating the relation between hydroelectric development and ecosystem impacts. What have we learned from past monitoring studies and can this inform us about the best balance between monitoring and focussed studies?
4. **What can we monitor vs. what we want to monitor**. Policy and legal requirements may dictate what should be monitored (i.e., the abundance salmonid fishes or species at risk), but are these the best candidates for evaluating the impacts of hydroelectric development, either from a practical (sampling) perspective, or from their likelihood of them being an ecosystem 'sentinel'? Is the use of ecosystem surrogates (i.e., riparian tree recruitment as a measure of flow regime suitability) likely to be acceptable to government and industry?
5. **How likely is a monitoring program going to be able to detect an environmental effect**? Simple population responses can be hard to detect given natural variability and measurement error and simulation studies suggest programs of long duration and high intensity may be required to be sensitive to anything other than catastrophic effects. Changes to complex ecological processes may be even harder to detect.
6. **Can monitoring be matched to the appropriate temporal scales of impact**? The impacts of hydroelectric development can be immediate (i.e., behavioural responses to flow changes), of moderate (decadal) term (i.e., changes to biota, communities), and long-term (i.e., geomorphological evolution of the river/reservoir). But most monitoring programs deal with the immediate impacts.

Is the monitoring and feedback loop of adaptive management the most practical means for dealing with the slower variables?

This list of issues suggests that considerable thought about why, how and what we are monitoring for needs to addressed before monitoring programs and adaptive management programs become enshrined in hydroelectric agreements. As well as the ecological issues the list clearly indicates the need for research on the policies, management structures and decision-making processes that will make monitoring and adaptive management an effective tool for water management.

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SUMMARY OF GROUP DISCUSSION FOLLOWING PRESENTATION

Following Mike Bradford's presentation on monitoring, the participants were encouraged to identify and discuss issues of relevance for Monitoring, particularly as they related to future research needs. A number of points and suggestions were identified.

- Decide whether monitoring is justified; may be better to pick a small number of specific subjects.
- Need a feedback loop between knowledge gained and adaptive management process; establish link between methods and timeframes.
- Need a specific plan for using the information.
- Establish clear objectives upfront and determine when monitoring would be finished.
- There is room to look at other data originally used for other purposes.
- Need a program that has flexibility based on learning from data collected; need meaningful and measurable changes.
- Difficult and expensive to identify all the resources/variables that require monitoring.

Fisheries Act Decision-making under Conditions of Scientific Uncertainty – acceptable levels of risk and uncertainty for hydro-electric projects

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ABSTRACT

This discussion paper was presented at a workshop in June 2004 convened between the Department of Fisheries and Oceans and the Canadian Electricity Association as part of on-going discussions established by the July 2002 DFO/CEA *Memorandum of Understanding* on the application of the *Fisheries Act* to hydro-electric generation. This paper discusses several challenges related to *Fisheries Act* decision-making associated with hydro-electric projects when conditions of scientific uncertainty exist. The paper briefly discusses approaches to risk management and suggests how social and economic considerations related to the hydro-electric industry could be integrated into *Fisheries Act* decision-making. Further areas of joint DFO-CEA research are identified.

INTRODUCTION

This paper discusses challenges related to *Fisheries Act* decision-making under conditions of scientific uncertainty. The specific focus is on the hydro-electric industry's interaction with fishery resources and how the inherent risks are assessed, managed and communicated to the public and industry. The objectives of this paper are to identify issues, promote discussion and suggest further areas of research.

EXISTING RESEARCH

This discussion incorporates principles and approaches outlined in various government policy papers on risk assessment, risk management and decision-making under conditions of uncertain science.

Extensive literature exists on the topic of risk management, public perception of risk and the communication of risk management decisions. The topic is complex so the intent of this brief paper is to identify several key issues that affect *Fisheries Act* decision-making, from the perspectives of both DFO and industry. Further research may follow as part of this joint DFO-CEA research initiative.

RISK MANAGEMENT APPROACHES

To assess and manage risk under conditions of scientific uncertainty, elements of the following approaches are commonly used, often in combination:

- Precautionary approach
- Risk trade-off and comparative risk analysis
- Adaptive management

Precautionary Approach

The 1992 *Rio Declaration on Environment and Development* Principle 15 is the most often cited formulation of the principle:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation. (United Nations 1992)

Canada has incorporated variations of this concept in recent legislation, including the *Oceans Act*, *Canadian Environmental Protection Act*, *Canada National Marine Conservation Areas Act* and *Species at Risk Act*. Various policy statements also refer to the principle. A comprehensive discussion is set out in *A Framework for the Application of Precaution in Science-based Decision making about Risk* ("*Precaution Framework*") which notes:

> The application of "precaution", "the precautionary principle" or "the precautionary approach" recognizes that the absence of full scientific certainty shall not be used as a reason for postponing decisions where there is a risk of serious or irreversible harm. The application of precaution is distinctive within science-based risk management and is characterized by three basic tenets: the need for a decision, a risk of serious or irreversible harm and a lack of full scientific certainty. (Government of Canada, 2003)

Risk Trade-off and Comparative Risk Analysis

Measures taken to avoid environmental harm in one area may displace harm to other areas. To minimize adverse effects on environmental resources while maximizing benefits from the use of those resources, the risks associated with a proposed activity should be compared to the risks associated with the reasonable alternatives to the activity. While this sort off risk trade-off analysis is desirable, it is not always practical in the context of every project that triggers the need for a *Fisheries Act* decision.

In a broader context, decision makers must also consider how best to allocate scarce management resources to where the need to reduce environmental risk is most pressing and will have the most benefit. A comparative assessment of the risks posed by various types of resource use may assist, but such an assessment is a major undertaking.

Adaptive Management

Adaptive management was developed by ecologists to accommodate uncertainty and complexity in ecosystem management. (Dovers and Mobbs 1997) One author describes it as "... the posing of *management-by-experiment* in complex, dynamic situations where controls and strict replication are not possible." Another author described it as "the formal process for continually improving management policies and practices by learning from the outcomes of operational programs." (Dunton 1998) The essential elements of adaptive management may be summarized as follows:

- Management interventions are made in an experimental manner so the outcome of the intervention can be used to reduce uncertainty about the system.
- Sufficient monitoring prior to and during the intervention enables detection of the results of the management intervention and thereby allows managers to learn from past experience.
- Management interventions are then refined, based on feedback to managers, communities and other constituencies.(Dunton 1998)

CONSIDERATIONS AFFECTING FISHERIES ACT DECISION MAKING RELATED TO HYDRO-ELECTRIC GENERATION ACTIVITIES

Hydro-electric Generation Industry in Canada

The hydro-electric industry plays an essential role in the production of energy in Canada. Canadian hydro-electric generation also competes internationally, providing much needed value to the economy. The recent experience with wide-spread electricity system failures in Canada and the United States has dramatically demonstrated our dependence on abundant reliable electricity. The resulting calls for renewed investment in generation and transmission illustrate the high social and political priority given to electricity generation. Hydro-electric generation plays a central role.

Much of the hydro-electric generation plant in Canada has been in place for many years, in many cases pre-dating current environmental regulatory standards, including important fish and fish habitat protection provisions of the *Fisheries Act* such as sections 32 and 35. Most hydro-electric generation operations, particularly those with reservoir operations, have some impact on fisheries resources that is unavoidable and incidental to their operation.

Industry's operational experience and understanding of the effects of hydro-electric operations on river systems is extensive. That collective industry experience is the principal reservoir of the knowledge base. Industry operators are at the leading edge of innovation in the area of risk management and techniques to mitigate operational impacts on the environment.

For the hydro-electric generation industry to be sustainable, significant capital investment is required to renew or expand the existing infrastructure to meet future energy demands. Capital investors require a clear understanding of the regulatory regime so they can understand the risks to their investment.

DFO Mandate and Resources

In a sustainable development context, optimal decision-making on resource allocation requires a careful balancing of the environmental, social, and economic dimensions. A comprehensive benefit-cost analysis can help identify the effects of proceeding or not proceeding with the project. Consideration of the foregone opportunities and the displacement of resources to or from other sectors should also be integrated into the decision-making.

DFO's mandate has an important, but narrow, focus:

> The Department of Fisheries and Oceans, on behalf of the Government of Canada, is responsible for policies and programs in support of Canada's economic, ecological and scientific interests in oceans and inland waters; for the conservation and sustainable utilization of Canada's fisheries resources in marine and inland waters; for leading and facilitating federal policies and programs on oceans; and for safe, effective and environmentally sound marine services responsive to the needs of Canadians in a global economy.(Fisheries and Oceans Canada 2001)

DFO is also guided by its policy on sustainable development:

1. The Department of Fisheries and Oceans is committed to sustainable development and undertakes to integrate economic, environmental and social considerations in the decisions it makes in carrying out its legal mandate, its policies and programs and its day-to-day operations.
2. The Department's commitment to sustainable development is based on the Department's Vision: safe, healthy, productive waters and aquatic ecosystems, for the benefit of present and future generations

> of Canadians, by maintaining the highest possible standards: of service to Canadians; of marine safety and environmental protection; of scientific excellence; and of conservation and sustainable resource use.
>
> 3. The Department is committed to continuous learning in its contribution to sustainable development and will monitor this commitment by reviewing progress toward its sustainable development goals on a regular basis and by taking corrective action as appropriate. (Fisheries and Oceans Canada 2001)

This policy also speaks of "integrated decision-making" that has a "long-term focus" and takes a "horizontal perspective" that incorporates economic, environmental and social aspects. (Fisheries and Oceans Canada 2001) These ideas were also recognized much earlier in DFO's 1986 Habitat Policy:

> The Department recognizes that natural resource interests such as the forest, fishing, mining, energy and agricultural sectors make legitimate demands on water resources, and that ways must be found to reconcile differences of opinion on the best use of those resources. Effective integration of resource sector objectives, including fisheries, will therefore involve cooperation and consultation with other government agencies and natural resource users.

The legitimate interests of other resource users will be considered in relation to the interests of fish and fish habitat to allow for reasonable accommodation, where possible. (Fisheries and Oceans Canada 1986)

Despite these powerful statements of intent, DFO's resources and expertise skill set do not often allow for a robust multi-sector assessment of the risk trade-offs associated with a *Fisheries Act* risk management decision. Nor is it always possible or practical for industry to undertake such an assessment in the context of every project. These constraints mean that the decision-making cannot be truly integrated with other economic, social and cultural interests in the fulsome manner contemplated by the existing policy documents.

To achieve optimal resource decisions, DFO would benefit from making full use of the industry's extensive knowledge base to resolve or minimize scientific uncertainty. The challenge is to do so without creating any perception that DFO's scientific and regulatory objectivity has been compromised. Also, industry must be able to trust that open sharing of information will not jeopardize its good regulatory standing.

Reconciling the current priorities related to fisheries management and conservation with the priorities of power generation creates a difficult challenge for fisheries managers. The complexity is compounded by the fact that DFO's is often the lead *Responsible Authority* under the *Canadian Environmental Assessment Act* review process. DFO is charged with the responsibility to make decisions that have far-reaching consequences beyond fisheries resources concerns, but does not have the mandate or the technical resources to undertake a broadly-based analysis.

REASONABLE LIMITS ON THE APPLICATION OF THE PRECAUTIONARY APPROACH WHILE MAINTAINING PUBLIC CONFIDENCE

Reduced to its simplest form, the precautionary principle reflects the adage: Better to be safe than sorry (Cross 1996). To many who are concerned about environmental values, this philosophy has great appeal and is often advocated on those simple terms. Applied without limit, however, this seemingly well-intentioned approach will lead to more harm than good to our environment, social infrastructure and economy. Among the negative results cited by one author are: direct physical risks; the risks associated with alternatives to the activity being prevented; and risks created due to a misallocation of resources. (Cross 1996)

Too great an emphasis on avoiding risk at all cost stifles change and innovation because the risks of new approaches are not as well known as existing ones. Such an emphasis systematically over-estimates risk which leads to a distortion of the true impact of the decision which, in turn, may result in resource decisions that are sub-optimal. Further, the approach ignores our economic and social needs, which are the other elements of the sustainability concept embedded in Government policy and DFO's mandate.

The need to acknowledge and manage risk to a level that conforms to our public and political values has been set out in the *Precaution Framework* as follows:

> Governments can rarely act on the basis of full scientific certainty and cannot guarantee zero risk. Indeed, they are traditionally called upon and continue to address new or emerging risks and potential opportunities, and to manage issues where there is significant scientific uncertainty. However, the need for decision making in the face of scientific uncertainty has grown both in scope and public visibility and this has led to a growing awareness of and emphasis on the application of precaution to decision making.
> While the application of precaution primarily affects the development of options and the decision phases within science-based risk management, it is clearly linked to scientific analysis (it

> cannot be applied without an appropriate assessment of scientific factors and consequent risks). Ultimately, it is guided by judgment, based on values and priorities but its application is complicated by *the inherent dynamics of science – even though scientific* information may be inconclusive, decisions will still have to be made as society expects risks to be addressed and managed and living standards to be enhanced. (Government of Canada 2003)

The economic and social consequences of allowing or disallowing the proposed action must be considered in risk management decisions. One author summarized the issue well:

> Without consideration of the economic boundary conditions, the precautionary principle is in fact a meaningless declaration of good intentions. Only by introducing the economic dimensions does it create the appropriate tension between human demands on the environment and the environment's need to be protected from such demands.(von Moltke 1996)

The weighing of economic and social factors is described in the *Precaution Framework*:

> While judgments should be based on scientific evidence to the fullest extent, decision makers should also consider other factors such as societal values and willingness to accept risk and economic and international considerations. This would allow for a clearer assessment of the proportionality of the measure and ultimately help maintain credibility in the application of precaution.(Government of Canada 2003)

The challenge in the exercise of the *Fisheries Act* public mandate on hydro-electric generation is to define the appropriate parameters for the application of a precautionary approach and then communicate those parameters to stakeholders.

DEFINING "RISK OF SERIOUS HARM" AND "SCIENTIFIC UNCERTAINTY"

The *Precaution Framework* lists three requisite tenets for the application of the precautionary approach:

- the need for a decision,
- a risk of serious or irreversible harm, and
- a lack of full scientific certainty

Need for a Decision

The need for a decision (or authorization) under the *Fisheries Act* is triggered only if certain prohibitions will be contravened by an activity, for example sections 32 or 35. Uncertainty and debate may arise when trying to answer this threshold question. If the effects of an activity are not fully known, then the need for a *Fisheries Act* authorization may also be uncertain. In most cases, DFO must assess the proposed activity at least so far as is necessary to determine the potential for harmful effects that would trigger the need for an authorization.

Risk of Serious or Irreversible Harm

Activity necessarily involves risk. The precautionary approach is only triggered, however, if the activity risks causing serious or irreversible harm. The appropriate use of the precautionary approach is to manage risk, not avoid it at all costs.

Distinguishing between real risk and perceived risk will be part of the risk assessment that DFO will undertake. While emphasis must be placed on the expert analysis of risk, often DFO may be obliged to take into account public perceptions of risk to address public concerns. In these situations, it will be important to communicate effectively to put the risks into proper context and scale.

Scientific Uncertainty

Scientific knowledge is constantly evolving and is, to some degree, always uncertain. When does sufficient uncertainty exist to trigger a precautionary approach? Inevitably, the assessment of the science is influenced greatly by the risks being considered.

Science can help establish the magnitude and probability of harm, but does not attach a value judgment to the outcome. That judgement is for the realm of social policy.

The *Precaution Framework* comments on scientific uncertainty as follows:

> Given the significant scientific uncertainty implicit in the application of precaution, follow-up activities such as research and scientific monitoring are usually a key part of the application of precaution.
> In other circumstances, scientific uncertainty may take a long time to resolve or, for practical purposes, never be resolved to any significant degree.
> Decision makers should assess such criteria as who holds the legal responsibility or authority (e.g., the proponent who is designated as the legal agent in Canada), who would be in the best position to provide the scientific data and who has the capacity to produce timely and credible information.
> While scientific information is still inconclusive, decisions will have to be made to meet society's expectations about enhancing living standards and addressing the potential for risks. (Government of Canada 2003)

Industry operators will often be the greatest source of expertise since they have the "hands-on" experience. The combination of technical experience and scientific analysis will help determine the degree of uncertainty and the implication of that uncertainty relative to the nature of the risk.

While project proponents bear the primary responsibility to furnish sufficient technical information to support their project, they should not be required to establish with absolute certainty that no harm will occur. Proving a negative can be impossible and, therefore, such a standard of proof is inappropriate. Moreover, imposing such a standard will distort decision-making so that innovation and change will be unduly constrained. The standard of proof should require the project proponent to prove that enough is known about the risks and the mitigation techniques to be comfortable that the risks are manageable to an acceptable level.

PUBLIC COMMUNICATION ON RISK MANAGEMENT DECISIONS – PUBLIC RISK PERCEPTION

A Privy Council Office paper on risk management notes the following challenges in the communication of risk:

> Particular challenges in developing a more integrated approach to communication and consultation activities throughout the decision process need to focus on several of the contextual aspects of risk:
>
> - the importance of perception or assessments;
> - degree of public tolerance for risk;
> - the role that pro-active risk communication (e.g. information, education) may play in building public understanding of risk and management of risk; and,
> - the need to gain/maintain public trust and its impact upon the credibility of government messaging. (Privy Council Office 2000)
>
> Among the public audience are also the industry members. Industry wishes to understand the regulatory regime so it can make informed investment decisions. An open and transparent decision-making process and clear decision criteria assist in the understanding of the regulatory regime. The *Precaution Framework* says the Framework is intended to strengthen and describe existing Canadian practice and to "improve the predictability, credibility and consistency of the federal government's application of precaution to ensure adequate, reasonable and cost-effective decisions".(Government of Canada 2003)

RISK ASSESSMENT FRAMEWORK

Several authors have described the need to introduce risk trade-off analysis (Cross 1996) or a risk prioritization (Fleming 1996) into the risk management decisions so that decisions match the true proportions of the risks.(see also Moffet 1997) This idea is also reflected in the *Precaution Framework,* as follows:

- The real and potential impacts of making a precautionary decision (whether to act or not to act), including social, economic and other relevant factors, should be assessed.
- Decision making should identify potential costs and benefits as explicitly and as soon as possible, and distinguish what risk the public is prepared to accept on the basis of sound and reasonable, albeit incomplete, scientific evidence.
- Consideration of risk–risk tradeoffs or comparative assessments of different risks would generally be appropriate, although this may not be possible in circumstances where urgent action is needed. This can ensure that society receives net benefits from decision making and that the application of precaution is inherently responsive to the potential from innovation or technological change and the overall benefits that such change can entail.(Government of Canada 2003)

DFO's limited mandate and resources constrain such a multi-sector analysis. This restriction has serious implications for the hydro-electric industry because of the narrow focus of the decision-making.

CONCLUSION

Acceptable levels of Risk and Uncertainty

Industry is concerned that precautionary approach is easily misunderstood and often misapplied. The precautionary approach should be a path forward to make informed and reasonable decisions on how to manage serious risks; it should not be used to avoid all risks.

Given the high societal priority placed on reliable power generation, the level of acceptable risk and uncertainty should reflect society's values. In practical terms, *Fisheries Act* risk-management decisions should reflect a careful balance between the priorities of fisheries management and prudent hydro-electric generation. The focus of the decision-making should concentrate in the first instance on “how to” proceed in a environmentally-responsible manner, and not default automatically to a focus on “whether to” proceed. This approach is consistent with the integrated decision-making model suggested by DFO's *Sustainable Development Strategy*.

Industry and DFO should collaborate to reconcile these priorities by ensuring that the best information is applied to the assessment of risk, making full use of the industry's operational experience and scientific expertise. Risk management tools such as adaptive management techniques offer opportunity to innovate and develop the industry, while managing risk within acceptable limits.

In the risk assessment process, the following considerations may help determine the acceptable level of risk and uncertainty:

- Prudently operated hydro-electric generation facilities may involve unavoidable necessary and incidental impacts on fish and fish habitat.
- Impacts should be considered on a regional or basin-wide basis to consider the overall net impact.
- Impacts should be assessed on population basis, not on individual basis.
- The costs and benefits of *Fisheries Act* decisions should be measured in terms of the impact on hydro-generation operation as well as the fisheries resource, particularly when determining the appropriate risk management options.
- Risk-management decisions that will seriously constrain operations, affecting their viability, must be taken at a senior level within DFO to ensure that the risk-trade offs among sectors are considered.
- Not all aspects of hydro operations have been studied in peer-reviewed scientific studies. Operational and technical experience must be given due weight in risk assessments.
- Risk management decisions should be results-oriented, rather than prescriptive, to allow for industry innovation in the mitigation of risk. As DFO's habitat policy notes:

  > Decisions should follow a results-based approach that considers professional judgment and common sense applied in a cooperative manner to seek effective and practical solutions.(Fisheries and Oceans Canada, 1986)

- The assessment of the options for managing the risk to acceptable levels should weigh the severity of the risk against the effectiveness and cost of the precautions.
- The opportunity to resolve the risk in the future with further experience or research should be considered.

Recommended Research

The following areas of further CEA-DFO collaborative research may help develop a stronger foundation for decision-making:

- Defining acceptable levels of risks for specific situations.
- Defining decision-making criteria that ensure that the risks and risk-management options are assessed in proper context so that the precautionary approach is applied appropriately.
- Developing risk management decision-making models that incorporate a risk-trade off analysis.
- Identifying constraints in DFO's mandate and governing legislation that inhibit broadly-based risk assessment that can take into account

the true cost and benefit implications of *Fisheries Act* risk management decisions.

- Identifying means to supplement DFO's mandate and resources to make broader assessments of the impact of its decisions under the *Fisheries Act* on the hydro-electric industry.
- Establishing a decision-making hierarchy within DFO that allows for the type of risk analysis required under the *Precaution Framework*.
- Establishing ways for DFO to collaborate with industry to share expertise and knowledge on the effect of hydro-electric generation operations on fisheries resources.
- Developing joint communication strategies to ensure that the public remains confident that the *Fisheries Act* mandate is maintained.

APPENDIX

Summary of the Principles from *A Framework for the Application of Precaution in Science-based Decision making about Risk*

A. Five General Principles of Application

1. The application of precaution is a legitimate and distinctive decision-making approach within risk management.
2. It is legitimate that decisions be guided by society's chosen level of protection against risk.
3. Sound scientific information and its evaluation must be the basis for applying precaution; the scientific information base and responsibility for producing it may shift as knowledge evolves.
4. Mechanisms should exist for re-evaluating the basis for decision and for providing a transparent process for further consideration.
5. A high degree of transparency, clear accountability and meaningful public involvement are appropriate.

B. Five Principles for Precautionary Measures

1. Precautionary measures should be subject to reconsideration, on the basis of the evolution of science, technology and society's chosen level of protection.
2. Precautionary measures should be proportional to the potential severity of the risk being addressed and to society's chosen level of protection.
3. Precautionary measures should be non-discriminatory and consistent with measures taken in similar circumstances.
4. Precautionary measures should be cost-effective, with the goal of generating (i) an overall net benefit for society at least cost, and (ii) efficiency in the choice of measures.
5. Where more than one option reasonably meets the above characteristics, then the least trade-restrictive measures should be applied.

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SUMMARY OF GROUP DISCUSSIONS FOLLOWING PRESENTATION

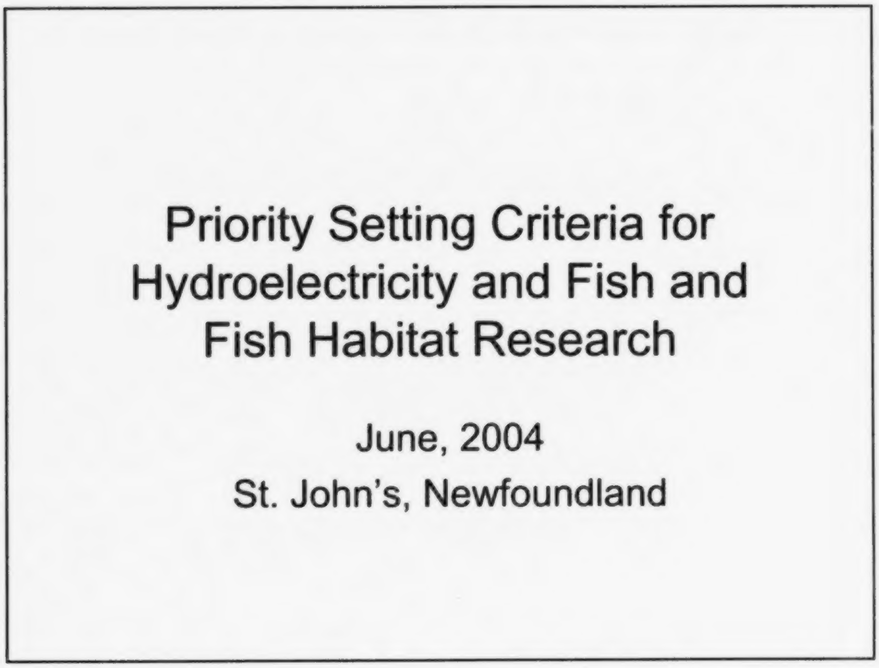
Following David Bursey's presentation on the importance of considering the role of uncertainty in the decision making process, the participants were encouraged to identify and discuss issues related to Scientific Uncertainty. A number of points and suggestions were identified.

- "No Go" decision may not be the appropriate automatic default.
- Boundaries need to be set on when to use precautionary principles so that they are used in the right context.

- Precautionary principle would apply to mitigation rather than go/no go decision.
- There may always be a level of uncertainty; the precautionary principle puts a lot of weigh on information that is missing.
- Need to determine what is reasonable based on probable outcomes.
- There are different circumstances with different consequences, different uncertainty and risk.
- Need to use the tools to manage risk overall.
- May need to accept new methods for compensation.
- Need to determine whether there is a way to filter significance of projects (minor/major) and to then adjust risk appropriately. Policy would help to determine the precautionary approach.
- Precaution would not be the only reason why a project might not be approved.
- There is an appropriate place to apply uncertainty – when have high risk/high consequence.
- Level of uncertainty is often related to only a small component of the project – may be experienced more on the fisheries side.

Presentation on Priority Setting Criteria

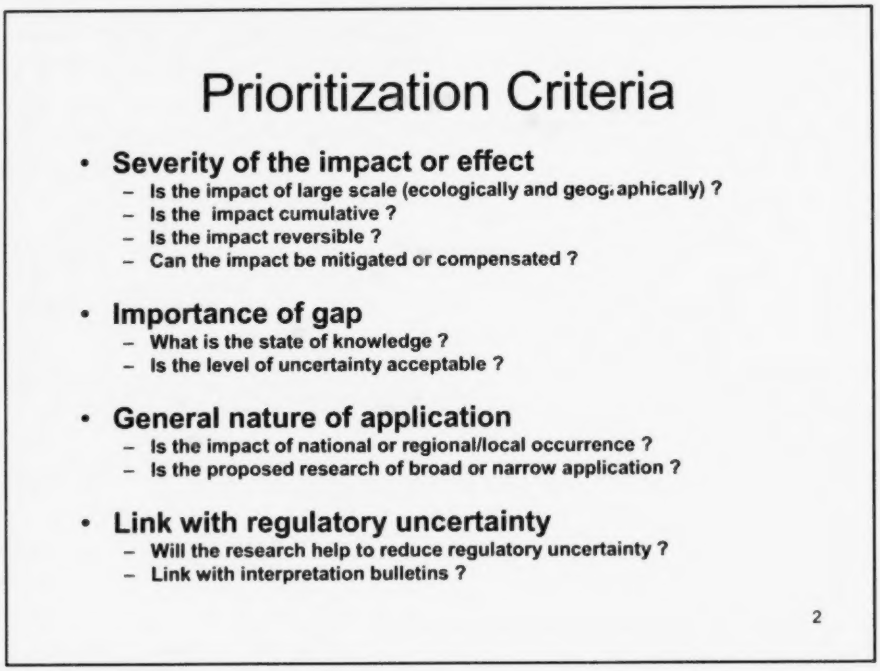
These are the slides from the presentation by Richard Verdon of the CEA, describing concepts involved in assigning priorities to potential research projects. This presentation was used to help guide the breakout groups in their thinking about the relative importance of science gaps, and the research projects needed to address those gaps.



Priority Setting Criteria for Hydroelectricity and Fish and Fish Habitat Research

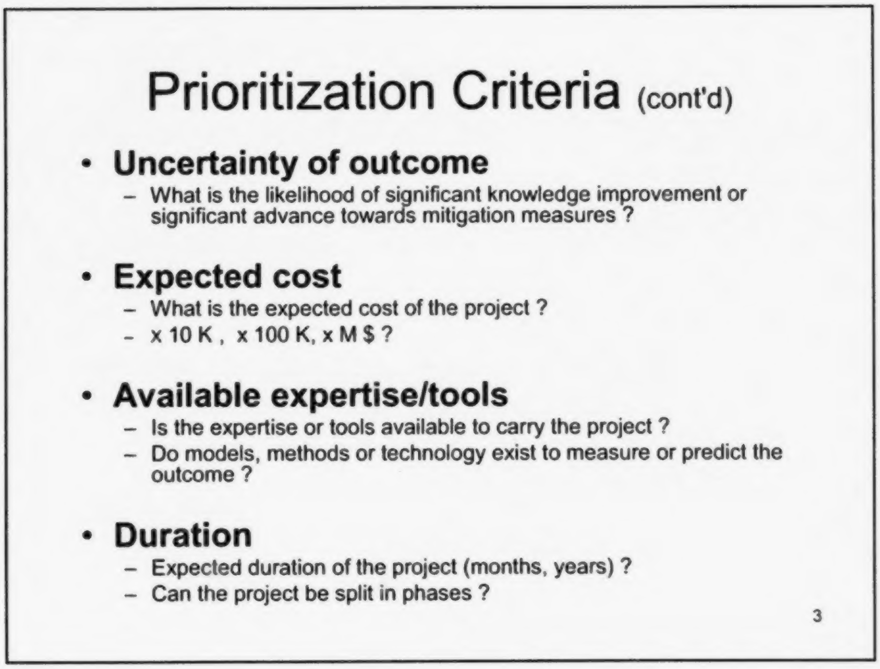
June, 2004

St. John's, Newfoundland



Prioritization Criteria

- **Severity of the impact or effect**
  - Is the impact of large scale (ecologically and geographically) ?
  - Is the impact cumulative ?
  - Is the impact reversible ?
  - Can the impact be mitigated or compensated ?
- **Importance of gap**
  - What is the state of knowledge ?
  - Is the level of uncertainty acceptable ?
- **General nature of application**
  - Is the impact of national or regional/local occurrence ?
  - Is the proposed research of broad or narrow application ?
- **Link with regulatory uncertainty**
  - Will the research help to reduce regulatory uncertainty ?
  - Link with interpretation bulletins ?



Prioritization Criteria (cont'd)

- **Uncertainty of outcome**
  - What is the likelihood of significant knowledge improvement or significant advance towards mitigation measures ?
- **Expected cost**
  - What is the expected cost of the project ?
  - x 10 K , x 100 K, x M $?
- **Available expertise/tools**
  - Is the expertise or tools available to carry the project ?
  - Do models, methods or technology exist to measure or predict the outcome ?
- **Duration**
  - Expected duration of the project (months, years) ?
  - Can the project be split in phases ?

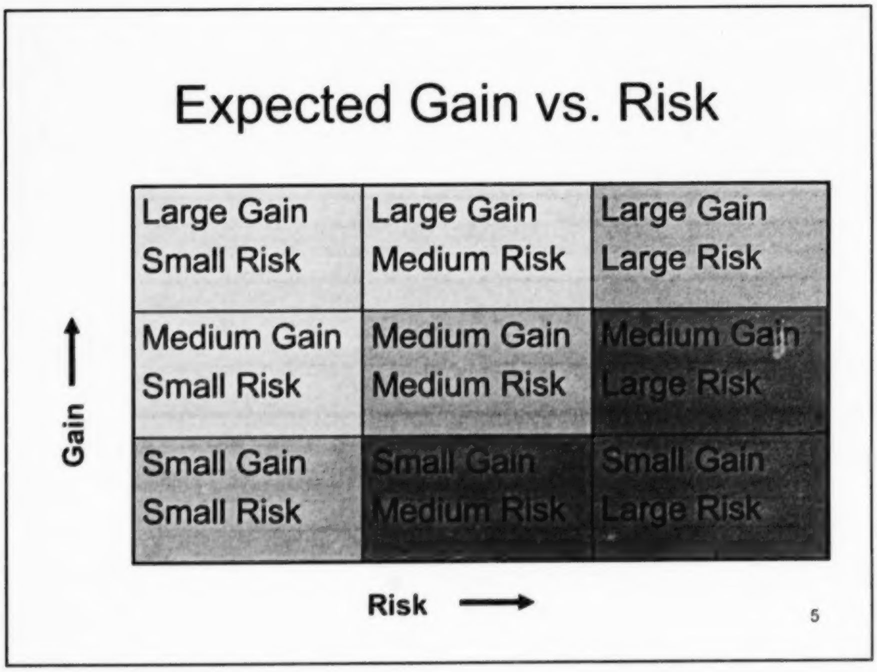
Prioritization Criteria

Gain criteria

- Severity of impact/effects
- Importance of gap
- General nature of application
- Link with regulatory uncertainty

Risk Criteria

- Uncertainty of outcome
- Expected cost
- Duration
- Available expertise and tools



Expected Gain vs. Risk

Large Gain Small Risk	Large Gain Medium Risk	Large Gain Large Risk
Medium Gain Small Risk	Medium Gain Medium Risk	Medium Gain Large Risk
Small Gain Small Risk	Small Gain Medium Risk	Small Gain Large Risk

Gain ↑

Risk →

Prioritization Criteria

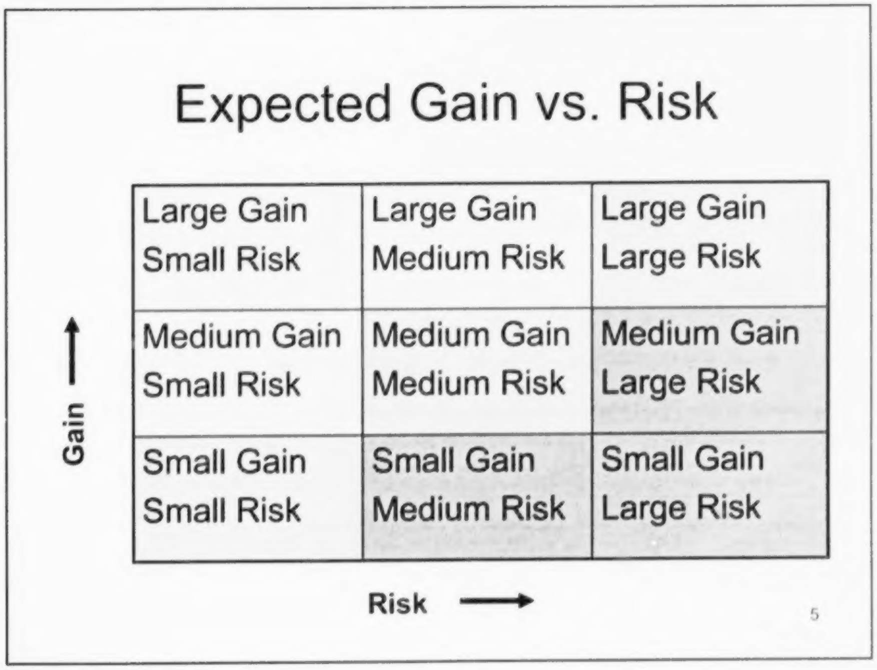
Gain criteria

- Severity of impact/effects
- Importance of gap
- General nature of application
- Link with regulatory uncertainty

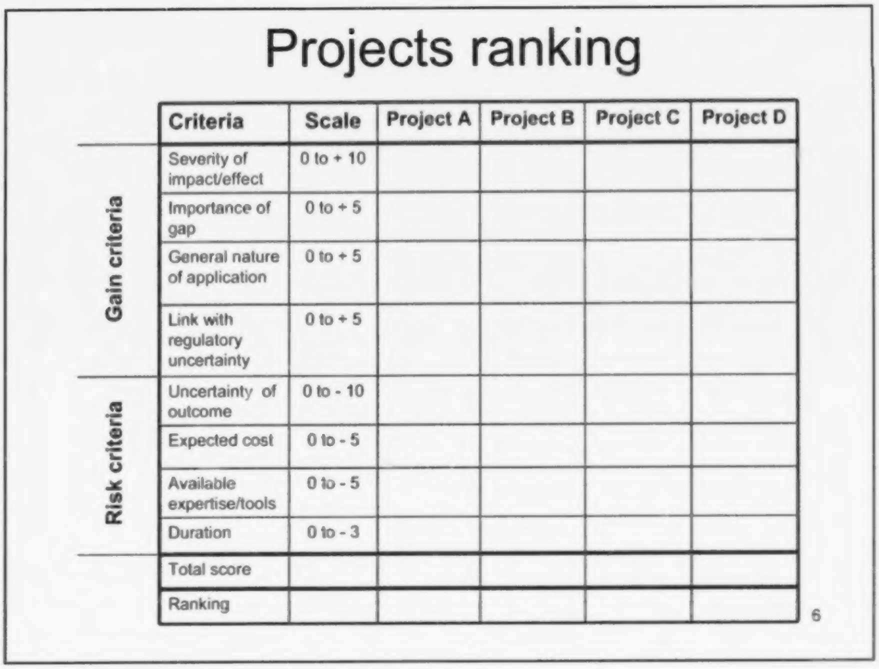
Risk Criteria

- Uncertainty of outcome
- Expected cost
- Duration
- Available expertise and tools

Expected Gain vs. Risk

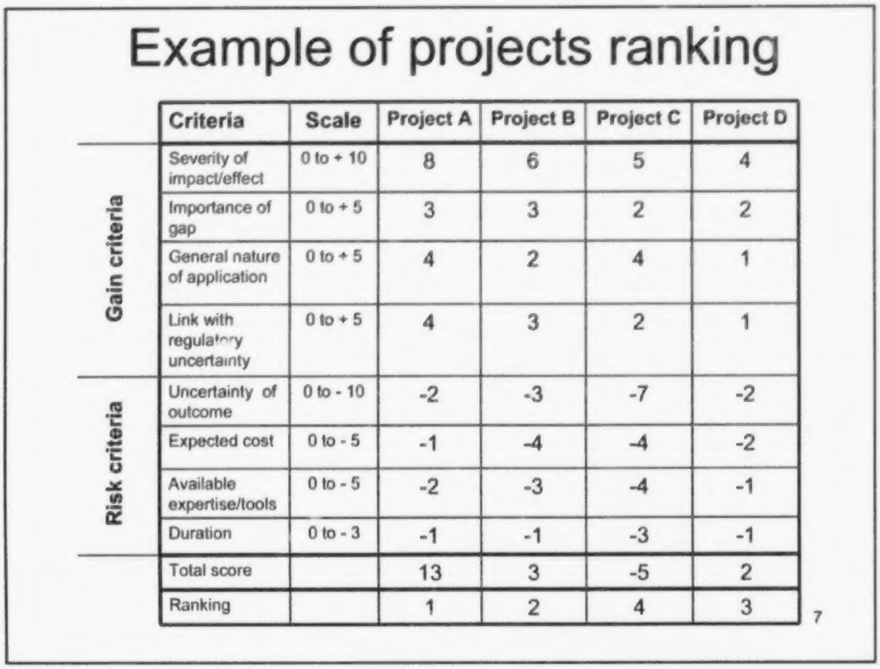


Large Gain Small Risk	Large Gain Medium Risk	Large Gain Large Risk
Medium Gain Small Risk	Medium Gain Medium Risk	Medium Gain Large Risk
Small Gain Small Risk	Small Gain Medium Risk	Small Gain Large Risk



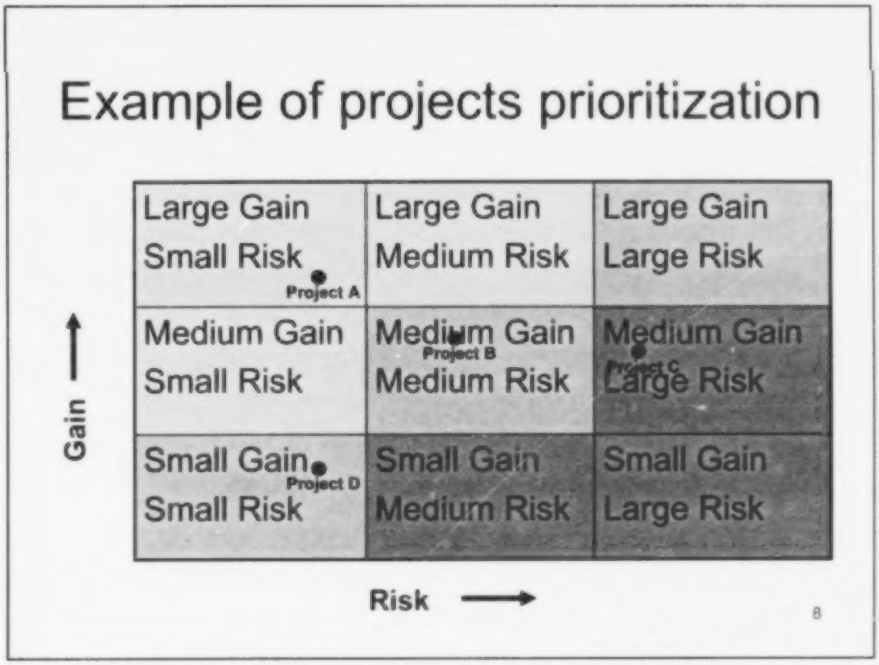
Projects ranking

	Criteria	Scale	Project A	Project B	Project C	Project D
Gain criteria	Severity of impact/effect	0 to + 10				
	Importance of gap	0 to + 5				
	General nature of application	0 to + 5				
	Link with regulatory uncertainty	0 to + 5				
Risk criteria	Uncertainty of outcome	0 to - 10				
	Expected cost	0 to - 5				
	Available expertise/tools	0 to - 5				
	Duration	0 to - 3				
	Total score					
	Ranking					



Example of projects ranking

	Criteria	Scale	Project A	Project B	Project C	Project D
Gain criteria	Severity of impact/effect	0 to + 10	8	6	5	4
	Importance of gap	0 to + 5	3	3	2	2
	General nature of application	0 to + 5	4	2	4	1
	Link with regulatory uncertainty	0 to + 5	4	3	2	1
Risk criteria	Uncertainty of outcome	0 to - 10	-2	-3	-7	-2
	Expected cost	0 to - 5	-1	-4	-4	-2
	Available expertise/tools	0 to - 5	-2	-3	-4	-1
	Duration	0 to - 3	-1	-1	-3	-1
	Total score		13	3	-5	2
	Ranking		1	2	4	3



Example of projects prioritization

Large Gain Small Risk	Large Gain Medium Risk	Large Gain Large Risk
Medium Gain Small Risk	Medium Gain Medium Risk	Medium Gain Large Risk
Small Gain Small Risk	Small Gain Medium Risk	Small Gain Large Risk

FRAMEWORK FOR MOVING FORWARD

Following Richard Verdon's presentation, a structured framework was created to more efficiently guide the group's discussions towards the development of a prioritized list of research needs, taking into consideration the criteria for prioritization.

Suggested Approach for discussion

A framework was suggested for discussion:

Goal: to build a knowledge base to make better decisions.

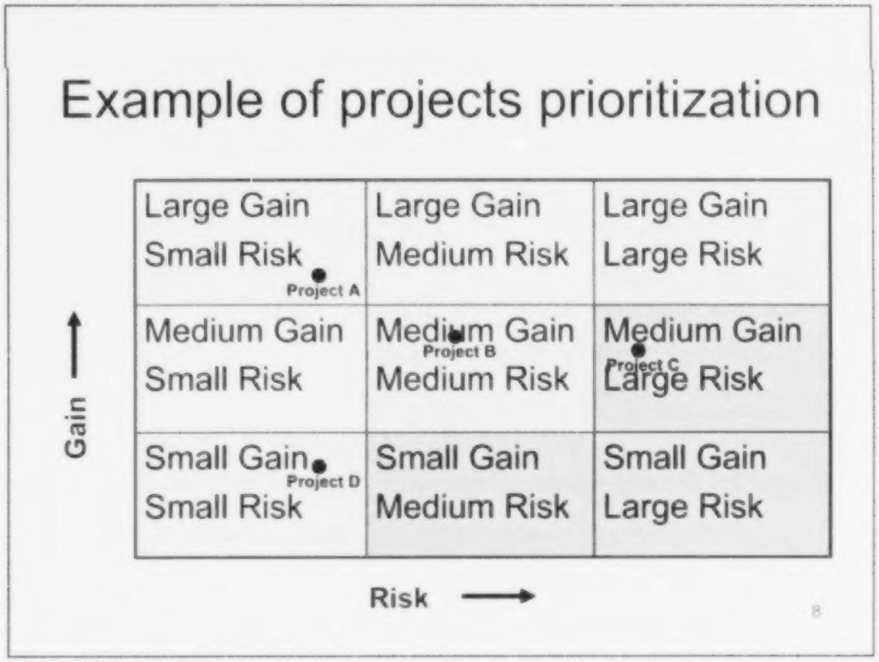
1. Case Studies
2. Monitoring
3. Research

Next Step: Develop Strategies

Discussion

The suggestion led to a number of discussion points and questions.

- Would it better to start with Case Studies?
- Should Gap Analysis be conducted as part of the framework – define priorities and questions?
- Were the prepared papers meant to start the setting?
- Is there a need to find ways to compare information?



Example of projects prioritization

Large Gain Small Risk Project A	Large Gain Medium Risk	Large Gain Large Risk
Medium Gain Small Risk	Medium Gain Project B Medium Risk	Medium Gain Project C Large Risk
Small Gain Project D Small Risk	Small Gain Medium Risk	Small Gain Large Risk

Gain →

Risk →

FRAMEWORK FOR MOVING FORWARD

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- Would it better to start with Case Studies?
- Should Gap Analysis be conducted as part of the framework – define priorities and questions?
- Were the prepared papers meant to start the setting?
- Is there a need to find ways to compare information?

- Need to decide on what areas should focus and where to fit things in.
- Were there areas of research already identified previously?
- Is the obvious beginning Case Studies and Framework?
- Case Studies exist for Fish Passage only?
- Case Studies are a tool, but may need to define the gap first.
- Would the next step be to build Interpretation Bulletins based on the gaps?
- Is it a two way process? – develop Interpretation Bulletin as well as use the information we have now.
- Must ensure that one aspect does not interfere with the other.

APPENDIX B: SUMMARY OF BREAKOUT GROUP DISCUSSIONS

Following the presentation on Priority Setting Criteria, the participants were divided into four groups with each asked to suggest the research priorities for one area of research: Fish Passage and Flow Modification, or Reservoir Science. The groups were encouraged, but not required to use the criteria for priority setting as presented. Each group presented its recommendations for discussion in a plenary session.

Fish Passage

Group Presentation Summary and Recommendations

Research Priorities – Case Histories

- Review & consolidation of fish passage experiences across Canada.
- Review of international fish passage experiences.
- While this is an important project, does not fit the criteria for research.

Research Priorities – General Considerations

- Natural fish passage efficiency vs. target fish passage (cost-effectiveness)
- Consideration of cleaning/maintenance costs for screens/racks
- Goals of fish passage vary by region

Identified High Priority Research Areas

- Fish attraction and fish guidance for upstream and downstream fish passage; generically how you would including:
  - Design for multispecies & life stage fishways
- Fish responses to hydraulic conditions, including:
  - Behavioural responses to hydraulic conditions
  - Facility location & transport in the river
  - Modelling of nature-like (physiomimetic) fishways
  - Hydraulics of new fish passage methods
  - Hydraulic conditions in fishways and at screens
  - Intake velocity & design to maximize fishway utilization, minimize injuries and prevent fish from entering turbines
  - Hydraulic anomalies
- Fish responses to hydrological variables
- Swimming performance & energetics

- Prevention of accidental downstream entrainment
- Fish-friendly turbine design

Criteria	**Scale**	**Attraction & Guidance**	**Hydraulic Conditions**	**Hydrologic Conditions**	**Energetics/ Swimming Performance**
Severity of Priority Setting impact/effect	0 to + 10	10	10	10	8
Importance of gap	0 to + 5	4	5	3	3
General nature of application	0 to + 5	5	5	5	5
Link with regulatory uncertainty	0 to + 5	5	5	4	4
Uncertainty of outcome	0 to - 10	0	-2	-2	-1
Expected cost	0 to - 5	-2	-2	-2	-2
Available expertise/tool	0 to - 5	-1	-2	-1	-1
Duration	0 to - 3	-2	-2	-2	-1
		19	**17**	**15**	**15**
Ranking		**1st**	**2nd**	**3rd**	**3rd**

Rankings

Discussion

After discussion, the participants agreed to the rankings as suggested by the group:

1. **Attraction & Guidance**
2. **Hydraulic Conditions**
3. **Hydrologic Conditions** tied with **Energetics & Swimming Performance**

It was agreed that the main priorities are still broad and will need more refinement. The issue and use of Case Studies was discussed. Several questions were noted:

- Will studies be used as a tool to fill the gaps?
- Can existing experiences and data be put together in a matrix? – would be very complex.
- Is more focus needed? – identify key areas and develop from there.
- What about access to international data base?

Flow Modification

Group Presentation Summary and Recommendations

Identified High Priority Research Areas with Ranking Score

- Natural flow paradigm Score 11
    - Winter flow impacts
    - Extreme event impacts coupled with current management practices
    - Production in pristine versus manipulated rivers
    - Ecosystem considerations
- Large river methodologies Score 4
    - Research methodologies
    - Meso-scale methodologies
    - More national focus
- Climate change impacts (operational & ecological) Score –9
- Comprehensive framework for Flow Management Score 19
- Peaking flow (load-following) methodologies Score 5
    - Validation of habitat models related to target species
    - Salmonids
    - Non-salmonid
    - Area specific
- Flow-habitat-population Score 8
    - Performance measures to determine success
    - Validation

Discussion

After discussion, the participants agreed to the rankings as suggested by the group:

1. **Comprehensive Framework for Flow Management**
2. **Natural Flow Paradigm**
3. **Flow – Habitat – Population**

It was noted that while the Comprehensive Framework for Flow Management was a high priority, it is outside the Research focus as it is not a knowledge gap. Also, some areas that had a lower rank were the result of an associated high risk (cost). It was questioned whether those lower rankings were indeed accurate or whether it was due to an incorrect ranking criteria.

Reservoir Science

Group Presentation Summary and Recommendations

Identified High Priority Research Areas with Ranking

• Habitat	Highest Priority

• Structure and type
  • Role of submerged trees/branches
  • Fish interaction
  • Creation/improvement	

• Changes in fish productivity and communities	Highest Priority
• Mitigative measures	Highest Priority

• Habitat
  • Erosion
  • Mercury clearing	

• Biological productivity	Highest Priority
• Mercury	Highest Priority
• Prediction • Baseline	
• Climate change effects	Lower Priority
• Reservoir operation effects	Highest Priority
• Drawdown • Erosion	
• Generation of climate-active gases	Lower Priority

Discussion

After discussion, the participants agreed to the following rankings:

1. **Habitat**
2. **Mitigative Measures**
3. **Reservoir Operation Effects**

These categories were acknowledged as a very good first step, but are still very broad. May need to ask the utilities for input. Additional key questions were proposed:

- What is the drawdown maximum?
- What are the erosion effects?
- What effect is there on the timing of bringing back up?
- What is the question around habitat – comparison with natural; link with productivity?
- Is the issue creation of new, existing, or both?
- What tool is needed to predict fish productivity?

RECOMMENDATIONS

The participants took the time to reflect on all of the information shared and to suggest a focus for moving forward. A number of recommendations were made.

- Overall it was acknowledged that the research categories are broad.
    - Need to define scope of work.
    - Need to define research questions.
    - Need to identify timelines.
    - Have to consider cost implications and funding sources/partnerships
    - Need to identify researchers.
- Need to move on the development of a Comprehensive Framework for Flow Management.
- Use Case Studies as a helpful tool.
- Need to prepare a product that identifies a list of experts.
- Group encouraged to consider active adaptive management as a tool for monitoring.
- Group was reminded that Research and Monitoring are part of the MOU.
- Need to acknowledge the differences that exist on regional versus national levels and to find an appropriate balance.

APPENDIX C: WORKSHOP AGENDA

CEA-DFO MOU Research Workshop

"Setting Research Priorities on Hydroelectricity and Fish or Fish Habitat: the MOU Research Agenda"

June 9-10, 2004
Fairmount Hotel, 115 Cavendish Square
St. John's, Newfoundland

FINAL AGENDA

DAY 1: WEDNESDAY, JUNE 9, 2004

Facilitator: Lynn Morrissey, Memorial University

8:00 – 8:30 CONTINENTAL BREAKFAST – Avalon-Battery Room

8:30 – 8:40 Introductions & Outline of Workshop Tasks:

Co-Chairs Hugh Bain, DFO Science & Richard Verdon, Hydro-Quebec

8:40 – 9:00 Fish Passage Presentation:

Chris Katopodis, DFO Science

9:00 – 9:30 Plenary Discussion

9:30 – 9:50 Flow Modification Presentation:

Dave Scruton, DFO Science

9:50 – 10:20 Plenary Discussion

10:20 – 10:30 BREAK

10:30 – 11:00 Reservoir Science Presentation:

Karen Smokorowski & Drew Bodaly, DFO Science

11:00 – 11:30 Plenary Discussion

11:30 – 11:50 Minor papers Presentation:

Monitoring – Mike Bradford, DFO Science & Paul Higgins, BC Hydro

11:50 – 12:10 **Plenary Discussion**

12:10 – 1:40 **LUNCH** (Buffet in the Fairmont Courtyard)

1:40 – 2:00 **Scientific Uncertainty Discussion paper:**

David Bursey, Bull Housser Tupper

2:00 – 2:30 **Plenary Discussion**

2:30 – 2:45 **Presentation on Priority Setting Criteria:**

Richard Verdon, Hydro-Québec

2:45 – 2:50 **Instructions for Breakouts**

2:50 – 3:00 **BREAK**

3:00 – 5:00 **Breakout Group Discussions on Prioritization (4)**

Breakouts 1 & 3: Fish Passage/Flow Modification

Breakouts 2 & 4: Reservoir Science

Each breakout group prepares a presentation for next day's plenary

5:00 **Adjournment** (Evening free for local entertainment)

DAY 2: THURSDAY, JUNE 10, 2004

8:00 – 8:30 **CONTINENTAL BREAKFAST – Avalon-Battery Room**

8:30 – 8:35 **Tasks for the Day:**

Co-Chairs Hugh Bain & Richard Verdon

8:35 – 8:45 **Presentation of Breakout Group 1**

8:45 – 8:55 **Presentation of Breakout Group 2**

8:55 – 9:05 **Presentation of Breakout Group 3**

9:05 – 9:15 **Presentation of Breakout Group 4**

9:15 – 10:15 **Plenary Discussion**

1. Prioritization of Areas of Research against ranking/scoring criteria
2. Prioritization of knowledge gaps within Research areas against scoring/ranking criteria

10:15 – 10:30 **BREAK**

10:30 – 11:45 **Recommendations and Next Steps:** Hugh Bain & Richard Verdon

11:45 **Adjournment**

APPENDIX D: WORKSHOP PARTICIPANTS

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